PHD

Shall I Compare Thee To A Pressure Wave? Visualisation, Analogy, Insight and Communication in Physics

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Visualisation, Analogy, Insight and Communication in Physics

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Thesis Abstract:

Do physicists ever find it difficult to get a mental picture of the physical processes involved in their research? What visualization techniques do physicists use to conceptualise & communicate physics? What are the perceived pros and cons of using such visualization techniques? This study explores such questions by combining qualitative and quantitative methods. These include, textual analysis of physics journal articles, public lectures, popular science books and magazine articles; an on-line survey of 225 physicists based primarily at universities across the UK and Ireland; follow-up e-mails with 13 respondents to pursue key findings from the on-line questionnaire; and an historical case study of a prize-winning physicist-engineer who used analogy to provide insights and bridge conceptual divides between specialists working in sub-fields related to accelerator physics.

My findings show that many respondents create or use sketches, physical/mathematical models, analogies and computer simulations as visualisation tools. Interestingly, some respondents prefer to work with images generated from the underlying mathematics, rather than images abstracted from phenomena witnessed in the world of perceptions.

A majority of respondents believed that computer simulations have strengthened physicists' visualization capabilities. They are particularly useful when dealing with unusual geometries and systems that are impossible (or extremely costly) to experiment upon in a 'real-world' laboratory.

I discovered that the forms of analogies employed by respondents were heavily dependent on the context of use (especially on the audience's expertise and the tone of discussion). Analogies containing a hierarchy of structural relations are particularly useful conceptualisation and communication tools.

The findings of my research will be of interest to practicing physicists interested in the conceptualisation and communication techniques used by their peers; science communicators interested in using 'good' analogies to make physics accessible to experts, intermediates and novices; and science educators interested in applying similar model-based reasoning skills in the classroom.

0.1 Physicists' Use of Analogy to Conceptualise & Communicate Physics

This thesis explores visualisation practices in physics, in particular, physicists' use of analogies as tools of exploration and explanation. Many physicists use analogy to visualise and communicate things that are beyond their sense perceptions - from positron interaction to galaxy formation. In drawing an analogy, physicists compare their subject matter to something else, (something more familiar, intuitive, tangible, visualisable etc.). Their hope is that this comparison, though imperfect, may highlight some of the essential features that their subject matter possesses, thereby providing insights. When popularising science, the goal is to offer insights to the audience by making physics accessible and memorable. Analogy is a useful explanatory tool in this context. Physicists also use analogy to explore new research areas and explain novel ideas to colleagues. Here, the initial insights gained by analogous reasoning can be further pursued and refined through rigorous mathematical, computational and experimental methods.

Research shows the importance of analogy as a means of providing and promoting understanding both in scientific discovery and in the communication of science (e.g. Bailer-Jones, 2002; Clement, 1991, 1994; Dunbar, 1995, 1999, 2001; Gooding, 1990, 2005; Gentner, 1983, 1989, 2005; Hesse, 1966; Holyoak & Thagard, 1995; Klahr, 2000; Miller, 2000; Nersessian, 1988, 2002, 2003). Nevertheless, further investigations are needed to uncover the **forms** of analogy used by physicists in different **contexts**. By forms I mean the sources from which physicists draw their inspiration (e.g. are they from physics, science, popular culture?), and the differing levels of abstractness of these analogies (are they mathematical, pictorial, physical or verbal?) By contexts I mean whether a physicist is employing analogy as (i) an **exploratory** tool in private conceptualisation and theory building, or (ii) an **explanatory** tool in communicating with experts, intermediates or novices, in formal and informal settings.

There is much evidence to suggest that playfulness and curiosity are important facets of creativity in science. Nobel Prize-winning physicist Richard Feynman (1997) emphasised this on numerous occasions. The revolutionary thinker Albert Einstein explained that "combinatory play" and "associative play" with "certain signs and more or less clear images" were essential features in his mechanism of thought (Hadamard, 1945/1996, pp.142-143). The developmental psychologist, Lev Vygotsky (1967) also believed that play was a vital component in helping children to develop the skills required to successfully engage in personal, professional and social activities. I wish to explore, among other things, the extent to which physicists employ playful analogies in private conceptualisation and informal discussions with colleagues to gain fresh insights. The scientific enterprise requires physicists to retrospectively reconstruct events to convey a logical, deductive approach to problem solving and experimentation. Thus, playful analogies are rarely published (cf. Kuhn, 1961, 1977; Gooding, 1990, pp.6-7). In fact, in section 5.8 I note that some journals censor the creative use of language. For example, Physical Review Letters' disapproval of Prof. Sir Michael Berry's use of two terms he coined: *"quantum chaology"* and *"diabolical points,"* despite the fact that many of his peers have adopted these terms.

Some scientists have discussed their creative insights in their diaries (e.g. Faraday) or when contributing to surveys on the issue (e.g. Einstein's conversations regarding his productive thinking with Gestalt psychologist Max Wertheimer, beginning in 1916; and more recently, Wolpert & Richards' collection of interviews with leading scientists of the time in their 1989 book **A Passion for Science**). For the most part, however, the abductive process, where new ideas are generated, remains in the shadows, edited out of the texts of science, revealed only through in-depth cognitive-historical case studies. Yet an understanding of the tools of exploration and explanation used by practicing scientists has applications in many areas, in particular science education.

0.2 Training Students to Think Scientifically.

My research shows that practicing physicists use both systematic and playful modelling techniques to conceptualise and communicate physics. Analogies, for example, can be used systematically - the underlying mathematics for one area of physics can be used to explore other areas of physics, e.g. the equations governing flow are analogous in electrical, mechanical, hydraulic and thermal contexts.[1] Analogies can also be used playfully – comparing a parallel plate resonator to a cheese sandwich attached to a stereo [2]; or likening positrons fired into a lattice from a particle accelerator to chickens fired into a forest from a cannon.[3]

There are of course drawbacks in employing analogy to conceptualise & communicate physics, as outlined by historians, philosophers, psychologists, and sociologists of science over the past 40 years.[4] As Hesse (1966) explains, models have **positive analogies** (e.g. the earth orbiting the sun in physical space is analogous to an electron orbiting the nucleus in phase space), **negative analogies** (e.g. the size of the sun is not analogous to the size of the nucleus), and **neutral analogies** (where the relation is not

[1] This is clearly highlighted in the table of "Interdisciplinary Analogies" in appendix 7.
[2] As Phys_193 does in section 5.4.1.
[3] As Prof. Paul Coleman does in his Dazed Chicken Model, presented in section 6.7.1.
[4] E.g. Hesse, 1966; Larkin & McDermott, 1980; Gentner, 1983; Gentner & Gentner, 1983; Nersessian 1995; Holyoak and Thagard, 1995; Taber, 2001.

known, e.g. the colour of the earth and the colour of the electron). By their nature, analogies are incomplete. It is the mismatch between source and target that enables play. Imprecise, fluid thoughts can be a source of possibilities for 'creative misunderstandings'. Unfortunately, less useful types of misunderstandings caused by analogy can be difficult to oust, as shown by Spiro, Feltovich, Coulson, and Anderson (1989) among others. The danger is to confuse the map with the territory: to think of analogy as an identity relation and mistakenly believe that the similarities between the two systems hold everywhere, on all levels.

The drawbacks of analogy are particularly evident in science education where novices fail to recognise the limitations of some analogies and consequently take concrete analogies too far. As Holyoak and Thagard (1995, p.204) caution: "[w]ithout guidance from a teacher, analogy is often a trap for the unwary novice, rather than a stepping stone to expertise." I have detailed the different forms of analogy used by **practicing physicists** in different contexts and have attempted to determine the **features of good analogies**. Thus, I believe that my findings will be useful to physics educators with an interest in training students to use model-based reasoning techniques similar to those used by practicing physicists. As Nersessian (1995, pp.204, 205) remarks: "we will be more successful at training students to think scientifically if they are taught, explicitly, how to engage in the modelling practices of those with expertise in physics." I believe that a searchable databank of good analogies (suggested by practicing physicists with a flair for communicating with experts, intermediates and novices) would be extremely useful to science educators. In order to compile such a databank, one must first determine the characteristics of good analogies. This project is a first step towards that end. As discussed in chapter 9, I hope to compile this searchable database in the future.

0.3 A word about terminology:

Considerable uncertainly surrounds the nature of mental images, representations, consciousness etc. (These issues are discussed in sections 1.2 & 1.3). However, my aim has been to explicate the visualization techniques employed by practicing physicists, not to answer philosophical or neurological questions. In order to carry out this empirical research I had to make certain simplifying assumptions. I began by assuming that the physicists under investigation have mental representations of the world, which differ in their complexity, vividness, realness, abstractness, and that these differences can be made accessible to investigation. For example, when considering atomic structure, one physicist may visualise billiard balls and another may visualise abstract mathematical structures.

Alternatively, an individual physicist may employ both visualisations, at different times, in different contexts. In order to gather information from these physicists it was necessary to employ words that would be meaningful to them. For example, the term 'mental picture' was employed in the initial survey to convey the idea of a visualisation or mental representation. As is evident from the wealth of data gathered, this approach proved successful: such terms were familiar enough to the physicists to be useful in eliciting responses, yet imprecise enough to allow for multiple interpretations. In fact, the various interpretations of terms such as 'research', 'analogy', 'visualizations', 'computer simulations', etc. revealed some interesting differences between sub-cultures of physicists, enabling me to refine the focus in follow-up studies.

Thus, throughout this thesis, unless specifically stated, the terms 'visualising', 'imagining' and 'envisioning' are all intended to mean 'forming a mental picture' and are distinct from the terms 'conceptualising' and 'conceiving of' which are intended to mean 'having an idea' (which may lack visual 'clarity'). For example, one may be able to conceptualise/conceive of infinity but not be able to clearly visualise/imagine/envision infinity. I share Dennett's (1990, p.299) view that, with practice, the distinction between conceptualising and visualising something becomes blurred, more or less vanishing when an individual achieves 'conceptual fluency' in navigating through conceptual 'spaces' constructed in the mind.[5] However, I differ from Dennett in that I hold an imagistic view of representation. This is discussed further in section 1.2.

0.4 Theoretical and Methodological Approaches:

Broadly speaking, my theoretical stance on the cognitive processes involved in analogical reasoning in science is that analogical reasoning involves a type of structure mapping or alignment between a source domain and a target domain. My aim is not to undermine the theory of analogy held by Genter (1983, 1989); Holyoak & Thagard (1995); Dunbar (1999, 2001); Klahr (2000); Spiro et al. (1989). Rather, I shall investigate the various *contexts* in which physicists employ analogy to provide and promote understanding. My methodological approach has been influenced by the fine-grained historical case studies of Gooding (1990, 1992, 2005), Gorman (1990, 1992), Gruber (1980), Miller (1984, 2000),

[5] Dennett remarks that according to Descartes, conceiving and imagining are quite distinct. What we cannot imagine we might well conceive. Descartes' famous example was the 'chiliagon': a regular 1000-sided figure, indistinguishable in imagination from a regular 999-sided figure. In Dennet 's view: "Conceiving of something complex – whether an abstract mathematical structure, a complicated physical process, or a system of rules or moves like chess or a grammar – is a matter of learning your way round in a 'space' you must construct in your mind. Only by actively exploring such spaces can we become familiar with them to the point of conceptual fluency, which is the point at which the Cartesian illusion is engendered of an act of direct conception. Getting to that level of fluency can be very difficult."(Dennett, 1990, p299)

Nersessian (1992, 1995), and Tweney (1985); the empirical laboratory investigations of Dunbar (1999, 2001), Gentner (1983), and Klahr (2000); the sociological studies of Latour (1987), Collins (1974), and Henderson (1995, 1991); the anthropological studies of Traweek (1988) and Forsythe (1993, 1994); and Myers' (1990, 1991) textual analyses of scientific writings.

As discussed in section 2.0, these methodological approaches all possess strengths and weaknesses. In an attempt to investigate novel research questions but avoid over reliance on any one method of investigation, I have chosen to employ a combination of qualitative and quantitative methods in order to construct a theoretical lens through which to view my material on a macro and micro level of investigation. These include a textual analysis of physics journal articles, public lectures, popular science books and magazine articles to uncover the forms of analogy in use in different contexts; an on-line survey of 225 physicists based primarily at universities across the UK and Ireland to gather empirical evidence from practicing physicists on issues surrounding visualization, analogy and computer simulations; follow-up e-mail exchanges with 13 of these questionnaire respondents to further explore some of the most interesting findings from the questionnaire; an historical case study of a prize-winning physicist-engineer (who is an enthusiast for analogy) in order to understand how the atmosphere in which he worked impacted upon the forms of analogy he used. My aim is to explore the various techniques employed by physicists to conceptualise and communicate in physics. My intention is not to offer law-like generalizations about creativity, innovation or problem solving.

0.5 Brief outline of thesis:

Chapter 1 addresses some key questions concerning mental representations. I critique some influential theories on the use of model-based reasoning in science and identify specific areas where a knowledge gap exists in the **literature**. Chapter 2 details the rationale behind the **methods** employed. I discuss the design and distribution of the on-line questionnaire, the analysis of the resulting data, and the selection of respondents for follow-up studies. I also provide the rationale behind the development of a cognitive styles framework as a tool with which to analyse my case study material. In Chapter 3 I focus on **visualization** in physics. Drawing on survey data and in-depth e-mail correspondence, I investigate the extent to which physicists report having visualization difficulties in their research and the reasons they give for this. I outline the many visualization techniques which this sample of 225 physicists report using and explore the extent to which visual imagination relies on kinaesthetic skills. Chapter 4 focuses on the use of **computer simulations** as visualization tools, as revealed by my survey data, follow-up e-mail correspondence with 13 questionnaire respondents and my semi-structured interview with Prof. Sir Michael Berry. Drawing on the same sources, in chapter 5 I explore physicists' use of **analogy in their research.** In chapter 6 I discuss the key factors that influence physicists' use **of analogy when communicating** with audiences of different backgrounds. Here I present survey data, follow-up e-mail correspondence with questionnaire respondents, as well as my observation of the analogies employed by Prof. Paul Coleman during his inaugural lecture at the University of Bath. In Chapter 7 I provide information on the educational, professional, social and cultural background of **Dr. John Lawson**, my case study respondent, in order to understand why he used certain forms of analogy in different contexts. Chapter 8 examines the means by which **'translator-physicists'** attempt to bridge 'linguistic' divides between 'sub-cultures' within the physics community. Again, the data stem from my case study of Dr. Lawson, a retired physicist-engineer. Chapter 9 contains a **summary and discussion** of the main findings, their implications, particularly for science education, and the scope for future work.

0.6 Summary of main findings

0.6.1 Visualization

As shown in section 3.2, initial findings indicated that two thirds of respondents have difficulty getting a mental picture of the various kinds of physical process involved in their research, somewhere between **"1/never"** and "**3**" on a 7-point semantic differential scale which runs from "1/never" to "7/always". **Subject area** was the most significant factor in determining the degree to which physicists experience visualization difficulties in their research. Factors such as (ii) **innate abilities,** (iii) **training,** and (iv) **experience** were less significant factors.

It is clear that some physicists' still experience difficulties getting a mental picture of the various kinds of physical processes involved in their research, but a majority are successful at overcoming these difficulties through personal or communal strategies, e.g. by employing analogies or computer simulations or by raising the concepts to a higher level of abstraction and visualising the form of equations rather than the physical processes which the equations are intended to represent. In section 3.8 I show that for many physicists, the kinaesthetic skills of drawing, modelling and reasoning by analogy are important aspects of their ability to visualise their subject matter. It is unclear to what extent these important skills are formally taught to physicists. Some physicists appear to develop these skills themselves prior to or in conjunction with their formal physics education. In my conclusions to chapter 3, I suggest that all physics students should be formally taught to generate analogies, build mental and physical models and (like some physics students and most engineering and architectural students) learn some basic drawing and drafting techniques to strengthen their tacit and visual skills.

0.6.2 Computer Simulations

In section 4.1 I show that there was a skew towards using computer simulations as visualization tools, with 48.2% of the sample selecting between **"5"** and **"7/all the time"** on the 7-point scale. In fact, the largest single group, 22.7% of the total, selected **"7/all the time".** In sections 4.2 – 4.5 I show that computer simulations are often used if the research involves: unusual geometries, several dimensions, numerous interacting parameters, huge search spaces, non-linear equations, complicated hardware/experimental design, microscopic or extraterrestrial systems which are impossible (or extremely costly) to experiment upon. Computer simulations are also particularly useful as a means of marketing physics: enlisting support from funding bodies, peers, and the general public by making good science look good. This is a less well-established function of computer simulations but an important facet of the scientific enterprise nevertheless. Computer simulations tend not to be used in areas that are easily visualised, or on the contrary, are at the edge of current theories – because, in the latter case, one lacks the equations and laws needed to create the computer code.

In section 4.4 I show that a majority of respondents indicated that computer simulations "7/definitely have" helped strengthen physicists' visualization capabilities both in respondents' **own research area** (51.6%) and **in physics in general** (52.5%). The minority of respondents who made selections on the negative end of the 7-point scale explained that computer simulations are used in numerical modelling, for example, <u>not as a visualization tool</u>, but instead to calculate outcomes. Thus, they do not necessarily strengthen one's visualization capabilities. In section 4.6.4 I note that many respondents stressed that computer simulations must always be used in conjunction with other physical methods, where possible. They emphasised that computer models should constantly be matched with experimental data. My interview with Prof. Berry highlighted the fact that computer simulations are powerful discovery tools, useful in developing geometrical intuition. However, findings from the on-line questionnaire and interview with Prof. Berry underscore the fact that computer simulations must be used cautiously, informed by studies of this kind that draw on practitioners' own experiences of what works and what doesn't work.

0.6.3 Analogy:

My research has shown that there are numerous and complex factors at play in physicists' use of analogy in the scientific enterprise. Firstly, there was no unanimous definition of what constitutes analogy. As discussed in section 5.1, some physicists appeared to hold a narrow interpretation of analogy, which excluded formal mathematical analogies. This may be because the term 'analogy' is usually associated with textbook physics or popular science books. (In fact the term metaphor was specifically avoided as it had poetic associations for some pilot study respondents). **Phys_185** explained: "[w]hat I use is often stronger than analogies, in that the underlying mathematical description is the same or similar in the first approximation. For example, harmonic waves appear all over the place in very different physical situations." However, many other physicists referred to harmonic waves and LCR circuits as exemplary analogies. In response to a follow up e-mail from me seeking clarification, **Phys_185** said that she may have interpreted the term 'analogy' more narrowly than I had intended.

I found these results somewhat surprising, as e.g. cognitive scientists' research on analogy has not emphasised this ambiguity of meaning amongst scientific experts who employ analogy on a daily basis. Acknowledging the ambiguity in the way expert physicists interpret the term 'analogy' may go some way towards understanding why some physicists are enthusiastic about the use of analogy to conceptualise and communicate physics while others disapprove of it. As **Phys_9** remarked: "Analogies may be perceived as a dumbing-down, humorisation or over-simplification of a concept; therefore they need to be used with care if the audience is already expert or 'stuffy'."

The second main finding concerning analogy was on the degree to which the **complexity** of the analogies related to the **context of their use**. Analogies on the <u>simple end of the scale</u> are common in (i) popularisations of science (e.g. one physicist compared quanta of energy in a quantum mechanical system to cents of euro in a monetary system in order to convey to novices the notion that energy is quantised), and (ii) playful exploration of new ideas (e.g. **Phys_134**'s mental image of a stadium helped him describe properties of D0-branes interactions). Analogies on the <u>complex end of the scale</u> are too sophisticated for physics novices to understand but are used by many physicists in their journal articles and conference talks. They are formal, mathematical analogies containing a high degree of isomorphism, i.e. there is a one-to-one correspondence between the structures at a certain level of abstraction (e.g. "to regard the exact renormalization group as a continuum analogue of blocking on a lattice." **Phys_170**). In the middle of the scale are analogies that combine aspects of both simple and complex analogies. They are highly idealised, have a certain degree of isomorphism, and have pictorial and/or physical features. They have a heuristic function and are used by experts and intermediates to extend existing knowledge into a new domain. The historical analogy between the flow of **heat** and the flow of **electric charge** is one such analogy. It has physical and pictorial components: both systems can be visualized as incompressible fluids flowing within channels. Consequently the mechanisms which bring about the phenomena in the analogous systems can be compared and contrasted. It also has a certain degree of systematicity – as the analogy does not break down when taken beyond surface similarity. My research provides evidence for Nersessian's assertion that: " ... analogies are not 'merely' guides to thinking, with logical inferencing actually solving the problem, but *analogies themselves do the inferential work and generate the problem solution*." (1992a, p.20, italics in the original)

Thirdly, my research shows that analogical reasoning is an extremely useful way of acquiring and providing *insight*. This can be: *pictorial insight*, i.e. creating visualizations of physical phenomena or of mathematical structures; or *physical insight*, i.e. helping one to get a 'feel' for how a system behaves by giving it a tacit, kinaesthetic component. This is discussed in some detail in my case study work presented in chapters 7 and 8.

The fourth main finding on analogy, and one which I believe will be of particular interest to science educationalists, was on the issue of **'mapping'.** The examples of original analogies offered by some respondents were similar to what Dunbar (2001) would call *long-distance* analogies, where the scientist maps from a commonplace *source domain* (a snickers bar or a cheese sandwich) to a more specialised target domain (a bar-shaped galaxy or a parallel plate resonator). This kind of mapping allows one to remember a key point in a very simple way. It acts as a scaffolding or framework within which to build one's theory or explain one's concept. I note that these kinds of playful analogies are particularly useful when marketing one's research to peers, funding bodies, prospective students and the general public. In sections 5.7 I suggest that some branches of physics may be more open to the use of physical and pictorial analogies than others, perhaps on account of the norms and conventions of the journals in their areas. In section 5.8 I suggest that some journals should be more accepting of physicists' use of creative language as a way of marketing their research to their peers and making the topic more engaging. For example, I believe that Physical Review Letters should re-consider its decision to censor

Prof. Berry's use of terms like "diabolical point" and "quantum chaology" because the terms have been intelligently constructed and are widely in use by Prof. Berry's peers.

In section 6.7.1 I argue that physically possible but implausible analogies can be useful in clearly highlighting the limitations of an analogy. Thus, they can be useful tools of explanation when dealing with intermediates and novices. I suggest that analogies which contain little literal similarity but much systematicity (i.e. the analogy holds for a hierarchy of relations from the underlying mathematical equations to the physical picture attached to the components of the analogy) are less likely to be promote a naive interpretation among novices, when used in a structured, integrated way, because novices realise that the analogies should not be taken literally. This finding therefore has implications for science educationalists, as it suggests a new approach to the use of analogies with physics students.

Fifthly, my research has led me to conclude that good analogies tend have some of the following features: (i) useful heuristics (i.e. rules of thumb) in problem solving; (ii) generative (i.e. suggesting new avenues to pursue); (iii) easy to express (pictorially, verbally, symbolically), (iv) useful in different contexts (formal & informal settings; with experts, intermediates & novices). On this last point, I believe that that analogies which span the whole range of contexts (from novices to experts, in formal and informal settings) are more often those with esteemed origins, i.e. they have been generated by eminent physicists with a flair for conceptualising and communicating physics.

In conclusion, my research clearly shows that analogical reasoning is an important model-based reasoning technique used by many physicists in order to bridge conceptual divides between experts and novices, scientists from different disciplines, and even specialists within the physics community; and also to 'promote' their research, i.e. to make their research accessible and memorable to peers, funding bodies, prospective students, and the general public, thereby enlisting support.

0.6.4 Implications of main findings:

The insights gained from my research should be of interest to practicing physicists interested in conceptualisation and communication techniques, and educators wishing to promote similar skills among physics students (particularly at secondary and tertiary levels of education). Analogy can be an extremely useful **exploratory** tool in scientific research: it can be used to generate insights and investigate properties of a model. Analogy can also be an extremely useful **explanatory** tool in communicating physics to experts, intermediates and novices, when the analogies are properly tailored to suit the audience. I believe that my findings, regarding the features of a 'good' analogies, may be useful to educators when devising or evaluating the likely efficacy of an analogy. When used in a structured, integrated way, analogies can provide experts, intermediates and novices with fresh insights that can be further developed through rigorous analytical means.

Most physicists surveyed believed that computer simulations have helped to *strengthen physicists' visualization capabilities* in their respective research areas and in physics in general. However, they warned that computer simulations should never be used 'black boxes' where their inner workings are unknown. If this happens, no useful insights can be obtained and computer simulations may actually weaken one's innate visualisation capabilities. This is a particularly interesting development, with possible implications for the use of computer software packages in tertiary levels of physics education.

0.7 Origin of Thesis Title:

Shall I compare thee to a pressure wave?

Visualization, Analogy, Insight and Communication in Physics.

I share Nelson Goodman's view the arts and sciences are similar in that they both: "... involve working with – inventing, applying, reading, transforming, manipulating – symbol systems that agree and differ in certain specific ways." (Goodman, 1976, pp.264, 265). With this in mind, my thesis title is a tongue-in-cheek blending of the opening line of Shakespeare's sonnet 18 with an analogy provided by a questionnaire respondent (**Phys_77**). In sonnet 18, Shakespeare searches for an appropriate analogy to highlight some of the essential characteristics possessed by the subject of his affections: *"Shall I compare thee to a summer's day? Thou art more lovely and more temperate ... "* I chose a Shakespearian sonnet because it has form and structure, a characteristic possessed by many analogies in physics, and because Shakespeare was both prolific and masterful in his use of metaphor & analogy in his literary works. As Spurgeon's (1936) studies have shown, Shakespeare's plays contain more than 6,000 metaphors (in the very extended sense, which includes analogy) and Shakespeare's work contains some 10 metaphors per page. **Phys_77**, meanwhile, compared an optical wavefront to a pressure wave because it, "becomes e.g. compressed when moving to a higher index medium." For example, a swimming pool looks shallower than it actually is because the optical wavefront changes direction (i.e. becomes refracted) on passing from air to water (i.e. its leading edge slows down on passing from a medium of low refractive index to a medium of higher refractive index). In re-formulating Shakespeare's sonnet, I surveyed the various examples of analogy provided by my respondents and chose a particularly suggestive one (pressure connoting stress, force, power, energy, etc.) which also had the correct number of syllables to maintain the sonnet's form and structure after substitution. The point I wish to make is that although conventionally thought of as polar opposites, physicists and poets are similar in at least one respect: both are creative in devising symbol systems with which to represent their subject matter. As Nobel Prize-winning physicist Neils Bohr[6] once remarked, the atomic physicist and the poet are engaged in a similar enterprise, "not nearly so concerned with describing facts as with creating images," because, "[w]hen it comes to atoms, language can only be used as in poetry." (Quoted in Bronowski, 1973, p.340)

[6] Bohr was one of the giants of modern physics who, in 1922, was awarded the Nobel Prize in Physics "for his services in the investigation of the structure of atoms and of the radiation emanating from them."

Chapter 1
Literature Review

The Road Not Taken

By Robert Frost (1874-1963)

Two roads diverged in a yellow wood
and sorry I could not travel both
And be one traveller, long I stood
and looked down one as far as I could
to where it bent in the undergrowth;
Then took the other, as just as fair,
and having perhaps the better claim
because it was grassy and wanted wear;
though as for that, the passing there
had worn them really about the same,
And both that morning equally lay
in leaves no feet had trodden black.
Oh, I kept the first for another day!
Yet knowing how way leads on to way,
I doubted if I should ever come back.
I shall be telling this with a sigh
Somewhere ages and ages hence:
Two roads diverged in a wood, and I--
I took the one less travelled by,
and that has made all the difference.

1.0 Providing a Map of the Territory

Explorations into scientific thinking began in earnest in the 19th century (e.g Galton, 1874; Cattell, 1910). In the intervening years this seemingly infinite territory has been explored by historians, philosophers, psychologists, sociologists, anthropologists, and science educators among others. Methodological and theoretical approaches have differed: these explorers have utilized different tools & maps, followed different streams of thought, and been guided by different stars. On the theoretical side, investigators have focused primarily on justification (e.g. hypothesis-testing), discovery (e.g. creativity, problem-solving etc.), and dissemination & acceptance of facts (e.g. representing novel phenomena, persuasion, education, etc.). On the methodological side, their investigations have ranged from sophisticated logico-philosophical arguments, to experimental/laboratory/*in vitro* studies; naturalistic/field/*in vivo* studies; computer models of scientific thinking; fine-grained historical case studies of renowned scientists and inventors etc. Mixed methodology studies have been in the minority. (An up-to-date review of these approaches can be found in Gorman, Tweney, Gooding, & Kincannon eds, 2005).

Exploring the territory in their wake, I have found footprints and signposts offering direction, abandoned vehicles and derelict encampments offering warnings, and bright lights offering hope. It is said that, "true exploratory research is really the working out of a winding trail into the unknown." (Du Vigneaud, 1952). To select novel research questions regarding scientific thinking, I followed a trail of literature that began in history and philosophy of science, and branched off into cognitive science, sociology of science, science education, literary theory, and even architectural design studies. Without knowing it, I was engaging in what Gruber (1980, p.292) would call a "network of enterprise". According to Gruber, this is where: "New lines of endeavour are differentiated, lines converge; parallels are recognized and fruitful cross-fertilizations occur; the individual responds to problems sensed in the world around him by undertaking new enterprises." Within the scope of this doctoral work, I could not pursue each path indefinitely. I kept 'the roads not taken' for another day, knowing that while way does lead on to way, I may someday come back.

The vastness of this interdisciplinary territory and the complexity of the sub-disciplinary terrain make it impossible to provide a detailed and accurate map within the scope of this thesis. Thus, for orientation purposes, I have presented an over-view of some of the literature in tabular form,[7] then discussed some areas of particular interest, placing my work at the confluence of several 'streams of thought', which I believe to be a fertile yet under-explored region.

My literature review revisits key areas of interest from historical, philosophical and psychological perspectives as it progresses. I start by discussing key cases of visual and kinaesthetic thinking in science from studies in the history of science. I then take a slight detour to present some philosophical and psychological views on mental representations. I return to visual and kinaesthetic thinking in science, exploring the specific roles of intuition, visualizability, insight and tacit knowledge in physics, drawing on literature in the fields of history, philosophy, and sociology of science.

Next, I provide a general overview of the creation and use of analogies and models in science, drawing on recent research by historians of science and cognitive scientists. I note that there are some excellent accounts of individual scientists' creation and use of models and analogies in science but few quantitative accounts of the extent to which contemporary physicists use them to conceptualise and communicate physics. Following on from this I suggest that it would also be useful to survey practicing physicists on whether computer simulations have strengthened physicists' visualization capabilities in their respective research areas and in physics in general.

I return to analogy again, reviewing the way in which it is understood and classified in the field of cognitive science. I suggest that there is a need to survey practicing physicists in order to investigate the forms of analogy they use in different contexts. With a view to performing a case-study of one physicist who used analogy to conceptualise and communicate physics, I look at the part cognitive, social, and developmental processes play in scientific thinking.

[7] The information is derived primarily from three works, which I found particularly useful for providing a concise summary of the state of the field: (a) Gooding, D.C., (2005), (b) Feist, G.J. & Gorman, M.E., (1998); (c) Goel,V., (1995). The literature reviews presented in the above works were used as a starting point, then adapted, extended, updated and re-presented in a thematic, tabular form, as can be seen in appendix 1

1.1 Visual and Kinaesthetic Thinking in Science: Key Cases From The History of Science

Francis Galton (1822-1911) investigated the thought processes of leading British scientists in the 1880s. Most of Galton's interviewees reported thinking in **words** rather than **images**. (Galton, 1883, pp.58- 60; see also Roe, 1951, pp.495-570). Ferguson (1992, pp.44-45) suggests that Galton, "a member of the aristocracy which took for granted its superior intellectual abilities... may have been a bit humbled when he learned that the people he met on the unexalted level of 'general society' were, like him, visual thinkers." Galton hypothesised that: "mechanicians, engineers, and architects possess the faculty of seeing mental images with remarkable clearness and precision... inventing their machines as they walk, and see[ing] them in height, breadth, and depth as real objects, and... in action." (Galton, 1883, pp.58- 60). He maintained the social divide between thinkers and doers by concluding that, "an over-ready perception of sharp mental pictures is antagonistic to the acquirement of habits of highly generalized and abstract thought." (ibid.) Yet, many 19th century scientists in Britain, including luminaries like Michael Faraday (1791-1867), Lord Kelvin (1824-1907) and James Clerk Maxwell (1831-1879) were undoubtedly **visual** and **kinaesthetic** thinkers, employing models and physical analogies extensively in their work. (cf. Kargon, 1969, pp. 423-436; Olson, 1975, pp.3-8).

The divide between thinkers and doers is also apparent in the remarks of French scientist and historian Pierre Duhem (1861-1916) who contemptuously contrasted the "ample" minds of English scientists with the "abstract" minds of the French. Duhem famously remarked that Oliver Lodge's [8] book on electrostatics contained nothing but: "... strings which move around pulleys, which roll around drums, which go through pearl beads... We thought we were entering the tranquil and neatly ordered abode of reason, but we find ourselves in a factory." (Duhem, trans. Weiner, 1962, pp.64, 70, 71). Duhem believed that these English physicists sought: "to create a visible and palpable image of the abstract laws," because the Englishman's "mind cannot grasp [these abstract laws] without the aid of this model." (Duhem, [1914] 1954, p.74). In contrast, Duhem held the view that "only abstract and general principles can guide the mind in unknown regions and suggest to it the solutions of unforeseen difficulties." (Duhem [1914] 1954, p.93).

[8] The scientific contributions of Sir Oliver Joseph Lodge (1851-1940) earned him the Rumford Medal of the Royal Society in 1898, a knighthood from King Edward the VII in 1902 and, in recognition of his pioneering work on wireless telegraphy, the Albert Medal of the Royal Society in 1919.

Yet recent studies in the history of science (e.g. Holton, 1978; Miller, 1984, 2000) have found that **visual** modes of thought (and for some **kinaesthetic** modes) also predominated amongst such giants of modern physics as Ludwig Boltzmann, Albert Einstein, Niels Bohr, Erwin Schrödinger, Enrico Fermi, Abdus Salam, Steven Weinberg and Richard Feynman. According to Root-Bernstein (1985, p.61), "most eminent scientists agree that non-verbal forms of thought are much more important to their thought processes than verbal ones."

Root-Bernstein also notes that van't Hoff, (recipient of the first Nobel Prize in Chemistry in 1901) identified a correlation between the sort of science produced by a scientist and whether or not he/she demonstrated non-scientific forms of creativity. Having studied more than two hundred scientific biographies van't Hoff concluded that the most scientifically imaginative scientists were almost always artists, poets, musicians, and/or writers as well. However, as Root-Berstein points out, any list of artist/scientists will always be incomplete, as some scientists, their biographers and archivists placed little emphasis on the importance of non-scientific aspects of a scientist's life. For example, none of the standard biographies of Louis Pasteur mentions his extraordinary artistic skill.

Recent work by Gooding indicates that there is: "a widely used visual method that relates human cognitive abilities to imaging practices in the sciences and the arts." (2004, p.1) Gooding's examples (which compare the visual methods employed in reanimation of fossils, reconstructive visualization in hepatology and stereographic projection in early X-Ray crystallography) clearly illustrate the patterned character of visual inference.

Root-Bernstein wonders, "to what extent visual imagination is dependent or independent of the kinaesthetic skills of drawing or modelling." (p.63) This issue is picked up in section 3.7, where questionnaire respondents remark upon the means by which they 'learned to see'.
Neuropsychologist Richard Gregory's (2001) work, on the design of interactive science centre exhibits, highlights the importance of **kinaesthetic skills** and **active touch exploration** in 'learning to see'. According to Gregory, the importance of active touch precedes humans: "There are many studies on animals showing the importance of active touch exploration for learning to see..." (web ref: Gregory, 2001, p.5).

Effective scientific experimentation and demonstration depends on learning about the world. For example, Gooding writes that, "Faraday's laboratory notes show him learning about the *minutiae* of electrostatic phenomena." (Gooding, 1992b, p.284). Faraday's success in learning about the world owed much to "sheer persistence and painstaking attention to the details of experiment" (Gooding, 1994, p.1042). In fact, Faraday prefaced the first edition of his first book "Chemical Manipulation, 1827" with Trevoux's slogan *"C'est n'est pas assez de savoir le principes, il faut savoir MANIPULER."* [9] (Quoted in Gooding, forthcoming in 2006, p. 5 of 24). Thus, fingertip knowledge gained through sheer persistence is required to obtain robust empirical results.

I share Gooding's view that, "thought experimenters must have learned enough about a world of one kind (through vision, touch and hearing) to access other, less familiar worlds." (Gooding, 1992b, p.285). We know that Einstein's insightful thought experiments often relied on **visual** and **kinaesthetic knowledge** drawn from the world of sense perceptions. For example, a 16 year old Albert Einstein imagined what he would see if he was riding on an electromagnetic wave. This thought experiment of 1895 ultimately led to his revolutionary paper "On The Electrodynamics Of Moving Bodies" in 1905. Then in 1907, Einstein imagined what would happen if he dropped a stone at the instant he stepped off the roof of his house. As Miller explains, this: "1907 thought experiment led to generalizing special relativity to measurements made in accelerating reference systems. This, in turn, required a folding together of geometry and physics with such astounding predictions as the bending of light near massive objects." (Miller, 2000, p.316). Thus, these two insightful thought experiments were instrumental in the development of Special Relativity and General Relativity.

Einstein said, in a letter to his friend the mathematician Jacques Hadamard, that: "The words or the language, as they are written and spoken, do not seem to play any role in my mechanism of thought." (Hadamard, 1945/1996, pp.142-143). Conventional words and other mathematical signs were "sought for laboriously" by Einstein <u>after</u> acquiring visual and muscular insights through what he termed, "combinatory play" and "associative play" with "certain signs and more or less clear images which can be voluntarily reproduced and combined." (ibid.)

Although Einstein's highly visual thought mechanism was the cornerstone of his revolutionary ideas in classical physics, it prevented him from fully accepting the highly abstract nature of Heisenberg's quantum mechanics in the 1920s. Both Einstein and Schrödinger agreed with Galileo's assertion that the book of nature is written in mathematics, but preferred to use visual imagery to represent mathematical symbols. They were not alone. Miller (2000, p.57) tells us that: "On May 27, 1926, Lorentz wrote to Schrödinger that ' if I had to chose between your wave mechanics and the [quantum] mechanics I would give

[9] This translates to: "It is not enough to know the principles, it is necessary to know how to MANIPULATE."

preference to the former, owing to its greater visualizability [Anschaulichkeit]'." Miller contends that Heisenberg's mode of thought, focusing on visualizability rather than visualization, "invites an adventurousness and play with visual imagery far beyond how this is carried out in classical physics, of which the relativity theories are essentially a part." (ibid.) Interestingly, Einstein conceived of no more seminal thought experiments after 1907. I share Miller's view that this may be related to the fact that:

> "research in atomic physics, as well as any moves beyond general relativity, required thought in a direction to which [Einstein] was not disposed, namely, toward visualizability (visual imagery generated by scientific theories) and not visualization (visual imagery generated from phenomena we have witnessed in the world of perceptions)." (Miller, 2000, p.319).

It seems that Einstein did attempt to adopt a less concrete form of thought when searching in vain for a unified field theory in his later years. However, the physicists Richard Feynman and Freeman Dyson have suggested that Einstein failed to develop a unified field theory "because he stopped thinking in concrete physical images [in his old age] and became a manipulator of equations." (Dyson, 1979, pp.75-76). Perhaps a thinker whose innate mode of thought relied on visual and muscular elements was conceptually blind, manipulating abstract mathematical equations in this way.

Feynman found a middle ground between Einstein's preference for concrete, physical images and Heisenberg's preference for abstract, mathematical formalism. Building upon foundations laid by Heisenberg's play with visual imagery, Feynman fused intuition and imagery with his invention of *Feynman Diagrams*. The visual imagery of Feynman diagrams is not abstracted from phenomena that have been observed, but generated by the mathematics of quantum mechanics. (cf. Muldoon, 2002, pp.30-31). However, physicists have always differed on the exact meaning of Feynman diagrams. According to Tian Yu Cao:

> "To Feynman himself, a diagram depicted an actual physical process in space-time, such as the exchange of photons that occurs when an electron and proton collide. However, he also saw it as a shorthand for the contributions to the amplitude of a physical process made by the element of the process depicted...In Dyson's view, the diagrams were useful to visualize mathematical formulae, rather than the actual physical processes of real particles." (Tian Yu Cao, 2006, p.36)

When 'translated' and championed by Freeman Dyson, the simplicity and intuitiveness of Feynman diagrams proved irresistible to most physicists of the era. (cf. Miller, 1984, p.170).

Interestingly, some years later, Feynman's difficulties visualizing electric fields led him to conclude that pictorial thinking had severe limitations. He explained:

> "I have a terrible confusion between the symbols I use to describe the objects and the objects themselves. I cannot really make a picture that is even nearly like true waves [...] When I talk about the electromagnetic field in space, I see some kind of superposition of all the diagrams which I've ever seen drawn about them." (Feynman, 1964, quoted in Gooding, 1992, p.144)

Gooding (1992) believes that there is confusion behind Feynman's conclusion that his inability to imagine electric fields proves the limitations of pictorial thinking.

> "Feynman assumes that one should be able to imagine the waves or establish their representational truth by comparing one's imaginings with the real thing. This rests on the familiar but mistaken conception of how representations (be they images, symbols or words) relate to what they are supposed to be about. This conception is mistaken insofar as it fails to recognize that the correspondence of representations to things in the world is a relationship made by human agency...To be sure, the images did come to stand for something in the world, but this was because they were *made* to do so – made, that is, through learning about how magnets, wires, and fields interact, how they may be represented, and so on." (Gooding, 1992, pp.144, 145) [10]

Almost forty years on, do physicists still report similar visualisation difficulties as those mentioned by Feynman? Have physicists overcome their visualization difficulties by some personal or communal strategy? For example, by externalising and disciplining visual images through the use of graphic notations such as Feynman diagrams? Is pre-existing kinaesthetic knowledge an important facet of 'learning to see' in certain branches of physics? As discussed in chapter 2, these questions are explored in the large-scale survey of practicing physicists, the follow-up correspondence with 13 of these respondents, the interview with Prof. Sir Michael Berry and the case study of Dr. John Lawson. As mentioned in section 0.3 my aim has been to explicate the visualization techniques employed by practicing physicists, not to answer philosophical or neurological questions. However, I will now provide an over-view of some of the philosophical and psychological perspectives on 'mental pictures' in order to situate my

[10] Gooding sums it up succinctly, in personal communication with Muldoon in October 2004, saying: "Feynman uses an attempt to visualize an e-m wave – which fails – to argue the limitations of visualization. But this is like arguing that, because climbing a ladder won't get to the moon, it is impossible to reach the moon. Feynman's mistake is to identify visualization with depictive mental images. But there are many kinds of images, and many functions other than picturing...Visualization ≠ vision."

work within an historical context and validate the terminology I chose to employ in my questionnaire.

1.2 The Theatre Of The Mind: Some Philosophical & Psychological Perspectives

For centuries, scholars have attempted to explain how the world is represented in our head. Aristotle believed it was impossible to think without images. Miller (2000,p. 265) notes that, "Plato compared mental images to impressions made on wax tablets and stored away for future use." In the 15th century Leonardo da Vinci compared the eye to a camera obscura – a dark box or room with a hole in one end, through which an inverted image of the world is projected. Two hundred years later, Johannes Kepler used his knowledge of geometry to detail the optics of the human eye. Kepler did not feel qualified to answer the question of how the image 'is made to appear before the soul.' (Lindberg, 1976, quoted in Blackmore, 2003, p. 80). René Descartes, however, attempted to do just this through an experimental approach which combined anatomical dissections with geometrical drawings. The details of Descartes' thesis did not stand the test of time however.

The 18th century Scottish philosopher, David Hume remarked that: "The mind is a kind of theatre, where several perceptions successively make their appearances; pass, repass, glide away and mingle in an infinite variety of postures and situations." (Hume, 1739, 1: 4: vi). Hume did caution against being deceived by the theatre of the mind metaphor, however, warning:

> "The comparison of the theatre must not misled us...They are the successive perceptions only, that constitute the mind; nor have we the most distant notion of the place where these scenes are represented, nor of the material of which it is composed." (Hume, 1739, 1:4:vi)

The 'theatre of the mind' metaphor continues in <u>common usage</u> to this day: we see with the 'mind's eye', make 'mental leaps,' processes happen 'outside' of consciousness, and so on. Many imagine that their inner selves are located somewhere inside their mind or brain; the outside world is projected onto a 'mental screen' and viewed with the 'mind's eye'; their senses transmit signals to an 'inner headquarters' where their inner self reacts to these stimuli. The theatre of the mind metaphor is also prevalent in many <u>psychological theories</u>. For example, conscious events are described by Baars (1988, p.31) as occurring "in the theatre of consciousness" or on "the screen of consciousness." According to physiologist-psychologist

Susan Blackmore (2003), what makes Baars' Global Workspace Theory, "more than just a loose metaphor is its grounding in psychology and neuroscience." [11] (Blackmore, 2003, p. 71). However, some theories of consciousness do jettison the theatre of mind metaphor completely, opting for somewhat more reductionist approaches. Daniel Dennett (1991, p.134) demolishes the theatre saying:

> "When you discard Cartesian dualism, you really must discard the show that would have gone on in the Cartesian Theatre, and the audience as well, for neither the show nor the audience is to be found in the brain, and the brain is the only real place to look for them."

Instead, Dennett proposes his 'Multiple Drafts Model'. Blackmore notes that according to this theory, "all kinds of mental activity, including perceptions, emotions and thoughts, are accomplished in the brain by parallel, multitrack processes of interpretation and elaboration of sensory inputs, and they are all under continuous revision...." (Blackmore, 2003, pp. 74-76)

Thus, as Motzkin, (2002, pp.206-207) notes, there are three main stances concerning representations: there are those who adopt a <u>logicist conception of representation</u> (i.e. representations take the form of explicit statements expressible in a formal language like the predicate calculus), those who maintain an <u>imagistic conception of representation</u> (representations take the form of images), and those who <u>reject the concept of representation</u> entirely.[12] Even within these distinct camps, the existence and nature of mental representations remain a topic of debate (e.g. Tye, 1991; Kosslyn, 1996). In experimental studies carried out by Shepard in the 1970s and 1980s, subjects were presented with pairs of figures and asked to indicate whether the shapes mapped onto one another if rotated through various angles. (cf. Metzler & Shepard, 1974). A correlation was found between the time taken to provide an answer and the time taken to mentally rotate the shapes. For example, shapes that had to be rotated by say 150 degrees took longer to elicit a reply, compared to shapes that had to be rotated by a few degrees. The subjects appeared to be mentally traversing an imagined

[11] Blackmore (2003) explains that: "The contents of consciousness are limited to the bright spot of attention, while the rest of the stage corresponds to the immediate working memory (Baddeley, 2000). The interactions between the stage, back-stage and audience are based on the idea of a global workspace architecture, first developed by cognitive modelling groups and common in computational approaches to human cognition. On this view, the brain is structured in such a way that just a few items at a time are dealt with in a global workspace – similar to the 7±2 items conventionally held in short-term memory. The theatre has numerous inputs from the senses and from the overall context, and connections to unconscious resources such as language, autobiographical memory and learned skills. According to Baars, all this provides a real 'working theatre', with consciousness acting as a gateway, providing global access to any part of the nervous system." (Blackmore, 2003, pp. 71-72)

[12] According to Motzkin, (2002, pp.206-207) "... cognitive scientists have adopted a logicist conception of representation, psychologists have continued to maintain an imagistic conception, and Continentals, true to themselves, have simply accepted the dissolution of the concept of representation, since they have concluded on the basis of the object's phenomenological constitution that the concept of mind is not relevant for philosophy."

distance. Psychologists speculated that the same areas of the brain were used for seeing and imagining. These speculations have been supported by experimental evidence in recent years. Magnetic Resonance Imaging (MRI) scans of the brain have shown that similar areas of the visual cortex are activated when looking at objects and when mentally rotating visual images. (cf. Kosslyn, 1988; Ganis, Thompson, and Kosslyn, 2004).

I have not gone into great detail on these philosophical and psychological views of mental representation because my main aim is to show that although multiple and opposing views of mental representations exist among philosophers and psychologists, the metaphor of a Cartesian theatre of the mind - the idea of 'seeing with the mind's eye' on a 'screen of consciousness' - persists. Thus, as I explain in the next section, it made theoretical and methodological sense to adopt this Cartesian theatre of the mind stance in my enquiries into the visualization techniques used by practicing physicists.

1.3 What Is My Stance Concerning Mental Representations?

Like many psychologists, I hold an *imagistic* conception of representation but, unlike them, my aim is not to uncover the cognitive architecture underlying representation, i.e. how are visual representations processed? How does an image refer to an imaged object? How are perceptions encoded? How are memories retrieved? For example, as Motzkin (2002, p203) asks: "If remembering is the remembering of perception, does that remembering encode perceptions as perceptions, does it store them as perceptions, and does it even retrieve them as perceptions?" Following the lead of researchers like Clement (1982, 1983, 1991), Collins (1974), Dunbar (1999, 2001), Galison (1996, 1997), Gooding (1990, 1992, 2005), Gorman (1990, 1992, 1998), Latour (1987), Nersessian (1992, 1995), Traweek (1988) and others, I am investigating representational practices in physics in order to uncover the visualization techniques employed by practicing physicists.

As mentioned in section 0.3, I maintain that internal representations may be *conceptual* and/or *visual*, e.g. one may be able to *conceptualise/conceive* of infinity but not clearly *visualise/imagine/envision* infinity. I share Dennett's view that with practice, the distinction between conceptualising and visualising something becomes blurred, more of less vanishing when an individual achieves 'conceptual fluency' in navigating through conceptual 'spaces' constructed in the mind. (Dennett,1990, p.299). I also agree with Dennett's assertion that, "There is no single act of the mind that counts as conceiving of something." (Dennett, 1990, p.298)

My simplified stance assumes a type of theatre in the mind, where one's consciousness (whatever that is) 'sees' the representations through the 'mind's eye'. I find this notion unsatisfactory on a philosophical and psychological level, but find it to be a useful **practical** alternative to assist me in my investigations into representational practices in physics. In order to enquire into the various representational practices employed by physicists, I needed to utilise terminology that they understood. The dissolution of the very concept of representation would have hindered my investigations because respondents' use of terms like *'mind's eye'*, *'mental picture'*, *'mental representation'*, *'pictorial representation'* etc. would have been meaningless in this context. Thus for the purpose of communication, it was vital to make some simplifying assumptions concerning representations.

For the purpose of simplicity I shall impose an artificial distinction between 'inner' and 'outer', categorising representations as either *internal* or *external (*cf. Hegarty, 2002, p.40 for a similar categorisation). *Internal representations* are constructed in a 'conceptual space' in the mind; they are remembered and inferred from perceptual and conceptual experience. A physicist, for example, may form an internal representation of: (i) entities perceived through the senses (e.g. a system of pulleys and weights, a fluid flowing through a network of pipes etc.); (ii) entities lying beyond the senses (e.g. electron-positron interactions, colliding galaxies); (iii) mathematical abstractions which do not correspond to physical entities and could therefore never be perceived through the senses (e.g. vector space, the structure of a mathematical equation, etc). *External representations* meanwhile are physical creations, capable of being perceived through the (visual, auditory, tactile, etc.) senses, e.g. textual descriptions, verbal descriptions, diagrams, schematics, photographs, paintings, scaled down models, static or dynamic visual output from computer simulations, video, etc. Thus, on this view *internal representations* are converted into *external representations* through externalising them in 'physical space-time'; *external representations* are converted into *internal representations* through internalising them in 'conceptual space-time'.

Representations play an extremely important role in cognition and communication in science. Gooding's (2005, p. 209) studies of representational practice in science reveal that images:

(i) "may be instrumental in generating new representation or in extending the use of existing ones;

(ii) enable and may also promote analogical transfers between different lines of inquiry that make up a network of enterprise;

(iii) symbolize an integrated model of a process that involves many more variables than the eye or the mind could otherwise readily comprehend. In these two cases visualization is essential to the construction and use of interpretative and analytical concepts."

As noted by Nersessian (1992b, p.30), static and/or dynamic representations "serve different cognitive functions." For example, visual representations of a highly idealized and abstract nature may be used to simplify solutions and convey quantitative understanding; artistic embellishments may be used to highlight specific features of phenomena; faithful reproductions and photographic images may be used to provide detailed and accurate accounts of biological systems; 3-D models may provide tacit awareness.

Interestingly, Trickett, Fu, Schunn, and Trafton's (2000) investigations have shown that, "[t]he external representations that are best for discovery are not necessarily best for communication of the discovery to others." (p.959) Representational practices usually involve simplification, idealization and abstraction; like *caricatures*, they emphasise certain features and suppress others, depending on the area of focus. Thus, for example, as Tversky (1999) remarks: "drawings reveal people's conceptions of things, not their perceptions of things." (Tversky, 1999, p.2, web ref.) The difference between perception and conception is an important facet of my thesis because many physicists deal with the abstract domain of quantum mechanics. Like sleepwalkers in a cosmic maze, these physicists must abandon their commonsense conceptions and learn new means of navigating through this shadowland lying beyond their perceptual experiences. Do contemporary physicists learn their way around this conceptual maze by visualising mathematical structures rather than the physical entities to which they refer? When dealing with quantum mechanics, must physicists rely solely on conceptions rather than perceptions? I will address this issue in section 1.4 below.

1.4 What Role Do *Intuition* and *Visualizabilty* Play in Physics?

According to Feferman (2000), geometrical and physical intuition can be cultivated through training and practice: "These may accord with tacit knowledge gained through experience, but, equally, one may gain intuitions that help one maneuver through subject matter that is initially highly non-intuitive." (p.317) Feferman emphasizes that there is no separation between intuitive knowledge and that obtained by systematic reasoning, saying that "they frequently go hand in hand, and neither is dispensable in practice." (ibid.) To what extent do contemporary physicists make use of (geometrical and physical) intuition in their work? What form does it take? Is it a component of **analogical reasoning**? I will address these questions in section 4.8.

Miller notes that, "In German, the word for intuition is *Anschauung*, which can be translated equally well as 'visualization'. To Kant, intuitions or visualizations can be abstractions of phenomena we have actually witnessed." (Miller, 2000, p.45). On the other hand, **visualizability** (*Anschaulichkeit*) refers to the properties of an object that exist whether or not we observe it or take measurements on it. As Miller explains: "The step of abstracting lines of force to entities that fill all of space and that are mathematically described by certain symbols in the equations of electromagnetism raises them from a visualizability to a visualization, from an *Anschaulichkeit* to an *Anschuung.*"(ibid.) In Newtonian physics, **visualization** and **visualizability** are synonymous but in quantum mechanics they are not. Miller quotes Heisenberg as saying that the basic problems of quantum mechanics in 1926 were rooted in the fact that one's, "ordinary 'intuitive view' " could not be extended into the atomic domain because, " 'The electron and the atom possess not any degree of physical reality as the objects of daily experience'." (Miller, 2000, p.59) In order to communicate with one another about the quantum world, physicists had to get by with the language of the macroscopic world. This was severely limiting. Heisenberg's quantum mechanics was based on non-visualizable particles, thereby avoiding any space and time description. According to Miller, "Heisenberg seemed willing to renounce visual imagery altogether and forever." (p.62)

Although some quantum physicists may adopt Heisenberg's approach when conceptualising their work, as the best-selling popular science author Fritjof Capra (1992) points out, they still face problems when trying to communicate their ideas to a non-specialist audience:

> " ...eventually they will want to talk about their results to non-physicists and will therefore have to express them in plain language. This means they will have to formulate a model in ordinary language which interprets their mathematical scheme. Even for the physicists themselves, the formulation of such a verbal model...will be a criterion of the understanding they have reached." (Capra, 1992, p.38)

How do physicists communicate quantum physics to intermediates and novices without employing mathematics? Are **analogies** used to bridge the divide between a concrete world of sense perceptions and an abstract world of quantum physics? [13] I will show in

[13] As Gooding (2005, pp.176-181) shows, there are of course many in-between stages of representation, i.e. quasi-concrete/perceptual.

chapters 5 and 6 that physicists often avoid seeking physical and pictorial descriptions when dealing with quantum mechanical concepts in their research. Instead, they must raise the concepts to higher levels of abstraction and visualize the structure of the mathematical equations governing the physics. Like Heisenberg, they opt for visualizability rather than visualization in their research. However, when communicating quantum physics to novices, many physicists do employ physical and pictorial analogies. Thus, the **forms** of analogies employed are highly dependent on the **context of use.**

1.5 What Role Does *Insight* Play in Physics?

Related to 'intuition' and 'visualizability' is the notion of 'insight'. Much of our vocabulary is peppered with words that equate sight with knowledge and understanding.[14] The meaning of the term 'insight' varies across subdisciplines, interpretations including: "an 'enlightening' moment when one suddenly 'sees' the solution to a problem" (Gruber, 1995, p.397); an understandable relationship (Köhler, 1947, p.326); the condition of possessing knowledge as opposed to the moment when knowledge is attained (cf. Gruber, 1995, p.398); or in Wallace's (1991) view a family of phenomena arising in creative work which includes: "problem finding… problem resolution, synthesis, discovering similarities, analogies, increase in certainty, recognizing error, the mot juste, and so on." (Gruber, 1995, p.398).

I think of insight as analogous to thunder and lightning: in a charged atmosphere, intellectual sparks fly, generating an initial flash of enlightenment. This is followed by a period of intense work to clarify the idea. The new idea then explodes onto the world, inducing initial confusion among onlookers. The conscientious scientist must devise a means of explaining his/her new idea to the world, through the use of such techniques as analogy, simulation, thought experiment, mathematical proof, experimental demonstration etc. The time delay between the initial flash and subsequent explosion depends on how 'far away' from the fully formed idea the creator was when s/he had the initial flash, and what the 'atmosphere' was like during the transformation from private 'little c' creativity to public 'big c' Creativity. Gardner (1993) and Boden (1990) distinguish between *'big-c'* Creativity and *'small-c'* creativity, where many people exhibit *small-c* creativity but only a few are *big-c* Creative. This notion also has associations with Csiksszentmihali two forms of creativity: (i) **personal creativity**, i.e. where an individual regards the product of their own work as

[14] Synnott (1993, p.208) provides the following litany: "insight, idea, illuminate, light, enlighten, visible, reflect, clarity, survey, perspective, point of view, vision, observation, show, overview, farsighted."

creative; (ii) **social-cultural creativity**, i.e. where others within the same society and culture regard the product of an individual's work as creative (cf. Yu-Tung Liu, 2000, p.267-269).

Early in my investigations, it became clear that acquiring 'insight' was extremely important to many physicists in their work. For example, as detailed in chapter 4, numerous questionnaire respondents mentioned the importance of acquiring 'insight' when asked about the pros and cons of using computer simulations as visualization tools. Throughout his scientific papers and during many of our interviews, my case study subject, Dr. Lawson, also frequently referred to the importance of acquiring 'physical insight' and 'pictorial insight', implying a distinction between the two, but finding it difficult to explicate this distinction during our follow-up discussions. This is discussed in chapter 8.

These early discoveries about insight prompted the following questions: How might *physical insight* differ from *pictorial insight*? For example, does physical insight incorporate a degree of *tacit knowledge* that may be absent in pictorial insight? What tools, techniques and problem solving strategies do physicists employ to acquire and promote insight? In particular, is **analogical reasoning** a useful means of acquiring and promoting insight? [15] These questions are explored in the case study in particular, discussed in chapters 7 and 8. I will now provide some background to the role of tacit knowledge in conceptualisation and communication in science.

1.6 What Role Does *Tacit Knowledge* Play in Acquiring and Promoting Insight?

In section 1.1 I noted that many historical case-studies have shown that many influential natural philosophers and physicists have relied on visual and kinaesthetic skills in their work. The physical chemist, Michael Polanyi was one of the first to highlight the importance of tacit knowledge in science. In his 1966 book, **The Tacit Dimension**, Polanyi explained that: "a mathematical theory can be constructed only by relying on *prior* tacit knowing and can function as a theory only *within* an act of tacit knowing, which consists in our attending *from* it to the previously established experience on which it bears." (Polanyi, 1966, p. 21). The work of Gooding, Tweney, Galison, Gorman, and Clement, among others, has also revealed the central role tacit knowledge plays in the enterprise of science.

[15] Gruber (1995, p.403) suggests that: "'I see!' is not quite the right ejaculation for such analogy-seeing. We might better say 'Look!'."

The sociologist of science Harry Collins defines tacit knowledge as: "knowledge or abilities that can be passed between scientists by personal contact but cannot be, or have not been, set out or passed on in formulae, diagrams, or verbal descriptions and instruction for action." (Collins, 2001, p.2). Collins' investigations into the role of tacit knowledge (and trust) amongst two groups of scientists leads him to conclude that the scientists' failure to transfer tacit knowledge, (on how to make measurements of the Q of sapphire), played a significant part in delaying the successful repetition of measurements for some 20 years.

My case study of Dr. Lawson, (chapters 7 and 8) will explore the extent to which he acquired insights by incorporating culturally acquired, tacit, kinaesthetic knowledge into physical analogies. I will also explore the communication techniques employed by Dr. Lawson in his journal and conference papers to provide insights to his peers: physicists and engineers who were experts in different sub-branches of physics, associated with the design of particle accelerators. This research question is discussed in section 1.7 below.

1.7 What techniques do physicists use to bridge 'linguistic' divides between 'sub-cultures' of the physics community?

As the late Diana Forsythe, (a cultural anthropologist of science and technology, with particular interest in the field of artificial intelligence) explained:

> "Culture defines what we take for granted, including explicit, formal truths of the sort embodied in scientific paradigms; the tacit values and assumptions that underlie formal theory; and the common-sense truths that 'everybody knows' within a given setting or type of setting." (Forsythe, 1993, p. 448)

According to science historian, Peter Galison, "Forms of work, modes of demonstration, ontological commitments – all differ among the many traditions that compose physics at any given time in the twentieth century." (Galison, 1997, p 782). Galison defines 'cultures' within the physics community as: "groups with very different systems of symbols and procedures for their manipulation" (ibid.) Thus, different fields of physics such as microwave tube, accelerator or plasma physics form 'sub-cultures' of physicists who utilise different mathematical notations, groupings of fundamental costants, codes (i.e. syntax and jargon) etc. Galison asserts that, "...even specialities within physics cannot be considered homogeneous communities." (ibid.).

A humourous means of highlighting the differing methodological appraoches, codes, syntax, notation, jargon/'languages' employed by 'subcultures' of the physics community is the infamous joke about, *"Hunting Lions in Africa"* [16]. The problem in need of solution is how best to catch a lion in the Sahara Desert. Eleven methods are proposed, each method charactisitc of a different sub-culture of the physics community e.g.:

- *"The thermodynamics method:* We construct a semi-permeable membrane which lets everything but lions pass through. This we drag across the desert."
- "*The Schrödinger method:* At every instant there is a non-zero probability of the lion being in the cage. Sit and wait."
- "*The Dirac method:* We assert that wild lions can ipso facto not be observed in the Sahara desert. Therefore, if there are any lions at all in the desert, they are tame. We leave catching a tame lion as an exercise to the reader."

A joke like this actually works on two levels: not only does it illustrate the many sub-cultures within the physics community, it is itself a code. One feels included, i.e. part of the 'tribe' when one 'gets' the joke, and excluded, i.e. an outsider, unfamiliar with the 'tribe's' language and conventions, when one doesn't 'get' the joke. Self-mocking creates solidarity: it identifies shared characteristics, shared experiences, shared world-views and shared foibles. Henderson, who has studied the visual culture of engineers, remarks that:

> "Restricted codes, such as the syntax and jargon used within social classes or work groups, are generated by social structures and serve to transmit culture. Restricted codes are predictable, simplified and narrow, impersonal, concrete, condensed, neither analytical nor abstract. While restricted codes limit vocabulary and flexibility, they also designate group solidarity." (Henderson, 1995, p.212)

The concepts of restricted and elaborated codes were initiated by Berstein (1971). We see that by limiting vocabulary & flexibility, these codes transmit culture, designate group solidarity, and facilitate communication <u>within</u> 'sub-cultures'. However, as my case-study respondent, Dr. Lawson, points out in the introduction to one of his conference papers (see section 8.2), a plurality of 'languages' can sometimes impede communication of ideas <u>between</u> 'sub-cultures'. Thus, a central research quesiton of this project is how experts bridge 'lingustic' divides between sub-cultures of physicsits and engineers. It is addressed through the survey (chapters 5, 6) and especially the case-study (chapter 8). I show that some physicists attempt to bridge 'liguistic' divides between subcultures of physicists and engineers through the use of **physical, pictorial and mathematical analogies** which 'translate' across these subdomains

[16] **Hunting lions in Africa** was originally published as **"A contribution to the mathematical theory of big game hunting"** in the American Mathematical Monthly in 1938 by "H. Petard, of Princeton NJ" [actually the late Ralph Boas]. See appendix 8, section A8.1 for an extended version. Thanks to Ed Trollope for suggesting that this joke might be relevant to my thesis.

and provide the practitioners with *insights*. As discussed in section 8.2, analogies, used in this way, have features in common with **conscription devices, boundary objects and construals in 'trading zones'**. I will now focus specifically on the creation and use of analogies in science, drawing on research in the related fields of history, philosophy and psychology of science.

1.8 The Creation and Use of Analogies in Science

According to Achinstein: "Analogies are employed in science to promote understanding of concepts. They do so by indicating similarities between these concepts and others that may be familiar or more readily grasped" (Achinstein, 1968, pp. 208-209). The usefulness of analogy has been recognised by many scientists in the past two hundred years. The eminent 19th century psychologist, William James, believed that: " men, taken historically, reason by analogy long before they have learned to reason by abstract characters." (James, 1890, vol . II, p. 363). He suggested that genius: "is identical with the possession of similar association to an extreme degree." (quoted in Ortney,1993, p.447). The 19th century natural philosopher Sir Humphrey Davy also recognised the importance of analogy, saying: "Imagination, as well as reason, is necessary to perfection in the philosophical mind. A rapidity of combination, a power of perceiving analogies, and of comparing them by facts, is the creative source of discovery." (Davy, 1840, p.308). Oppenheimer, a distinguished physicist from the 20th century, highlighted the importance of analogy in science, giving it the qualities of a tool or instrument. In his own words: "Science is an immensely creative enriching experience; and it is full of novelty and exploration; and it is in order to get to these that analogy is an indispensable instrument." (Oppenheimer, 1956, p.130) The linguist, Max Black (1962) suggests that metaphors are perhaps a necessary preclude to theory-making: "Perhaps every science must start with metaphor and end with algebra; and perhaps without the metaphor there would never have been any algebra." (Black, 1962, p.236). According Alan Gross, (a specialist in communication studies) metaphor and analogy never disappear outright. He says that, "Although the official view is that metaphor and analogy have only a heuristic function, that they wither to insignificance as theories progress, tropes are central to the scientific enterprise, and never disappear altogether." (Gross, 1996, p.18)

Miller's (1984, 2000) insightful case studies in the history of scientific thought illuminate the role of metaphorical and analogical reasoning in physics. Miller's examples suggest, firstly, that metaphors and analogies provide a means of seeking literal descriptions (i.e. scientific theories) of the world around us. Secondly, the comparison property of metaphors and analogies brings the distinction between theory and model into sharp focus. Thirdly, metaphors and analogies underscore the continuity of theory change while the ontology (i.e. the reality status of something) remains fixed (cf. Miller, 2000, p.219).

As mentioned in section 1.1, physical and pictorial analogies have helped many physicists (e.g. Kelvin, Maxwell, Faraday, Einstein) to visualise unseen mechanisms and thereby get a handle on things (quite literally in the case of mechanical models of physical systems). Of course, as Miller (2000) points out, the physicists who have employed these physical and pictorial analogies throughout history did not believe that the electrons constituting matter were attached to springs, or that the electromagnetic theory had anything to do with wheels and pulleys. These conceptualisations were merely used to build a framework within which to explore, discover, develop and explain novel concepts. As discussed in section 1.8 models (often built upon analogies) are used iteratively by scientists. The initial pictorial and physical insights are extended, developed and tested via more formalised, analytical means. For example, Nersessian (1992) details how Maxwell adapted and honed his analogies as his understanding, of the target domain onto which he was mapping, grew and deepened. According to Gorman (1995), Alexander Graham Bell's mental model for his telephone closely followed the analogy of the human ear. Like Maxwell, Bell continually modified the analogy as he learned more about his target domain. There is often a movement from pictorial and mathematical modes of expression to verbal modes of expression as scientists move from problem solving to dissemination of results.

Michalski (1989, p.127) argues that it is more difficult to notice analogy than to use it once it has been observed because the former involves *induction* while the latter involves *deduction.*[17] I would argue that reasoning by analogy actually involves "abduction". In the Peircian view: "Deduction proves that something *must* be; Induction shows that something *actually* is operative; Abduction merely suggests that something *may be.*" (quoted in Hanson, 1965, p.85). My research will fill a gap in the literature by gathering empirical data on the extent to which practicing physicists use analogy to conceptualise and communicate physics, and generate original analogies. I also devise a form of classification to explicate the forms of

[17] "The process of noticing analogy and creating an analogical mapping between two systems is intrinsically inductive; the process of deriving inferences about the analog using the mapping is deductive….This view of analogy as induction and deduction combined explains why it is more difficult for people to notice analogy than to use it once it is observed. This is so because inductive inference, being an underconstrained problem, typically consumed significantly more cognitive power than deductive inference, which is a well-constructed problem." (Michalski, 1989, p.127)

analogy employed by physicists in different contexts. Thus, I believe that my empirical data will be of interest to philosophers of science who are interested in shedding light on the abductive process in science.

So although previous research (Dunbar, 1995, 1999, 2001; Gooding,1990, 2003, 2005; Gentner, 1983; Hesse,1966; Harré,1988; Klahr, 2000; Nersessian, 1988;) established the importance of analogy as a means of providing and promoting understanding both in scientific discovery and in the communication of science, further investigations were needed to uncover the forms of analogy used by physicists in different contexts. By forms I mean the sources from which physicists draw their inspiration (e.g. are they from physics, science, popular culture?), and the differing levels of abstractness of these analogies (are they mathematical, pictorial, physical or verbal?) By contexts I mean whether a physicist is employing analogy as an exploratory tool in private conceptualisation and theory building, or an explanatory tool in communicating with experts, intermediates or novices, in formal and informal settings. I address these research questions through my large scale survey of 225 physicists in particular. The data is presented in chapters 5 and 6.

1.9 The Creation and Use of Models in Science

A central aim in this project is to provide an account of how practicing physicists create and use **analogy** as one strategy or method of **modelling.** This research question is addressed via the large-scale survey and case study. The research design is outlined in chapter 2 and the findings presented in chapters 5 to 8.

The creation and use of models has been a central facet of the scientific enterprise in England for well over a century. As mentioned previously, Duhem tells us that contemporary 19th century English scientists frequently relied on models to explicate their theories, contemptuously contrasting the "ample" minds of the English with the "abstract" minds of the French. (Duhem, [1914] 1954, p.69) Duhem wrote:

> "Understanding a physical phenomenon is, therefore, for the physicist of the English school, the same as designing a model imitating the phenomenon; whence the nature of material things is to be understood by imagining a mechanism whose performance will represent and simulate the properties of the bodies." (Duhem [1914] 1954, p.72).

On the positivist view, reasoning involves applying a set of rules. The equations and definitions make up the complete description of a scientific theory. As Nersessian (1995, p222) explains, on this syntactic view, "A conceptual structure is a set of definitions, the proper formulation of a theory is as an axiomatic structure and reasoning with the theory is deductive, reasoning to the theory is inductive." However, model creation, via abduction, may be at the heart of novel discoveries in science. According to Peirce: "Induction sets out with a theory and it measures the degree of concordance of that theory with fact. Induction never can originate an idea whatever. No more can deduction. All the ideas of science come to it by the way of Abduction." (Peirce, quoted in Hanson, 1965, p.146).

Hutten (1954, p.285) believed it was important to reconcile scientists' and philosophers' accounts of scientific method. At that time, philosophers paid little attention to models, despite the fact that scientists' accounts of scientific method emphasised the importance of model-based reasoning. As Hutten remarked: "It is obviously best to follow the scientists here as closely as possible, at least in the first instance; we may hope in this way to avoid forcing science into a pre-conceived scheme, as philosophers have so often done" (Hutten, 1954, p.81). Many contemporary philosophers and historians have taken Hutten's advice to heart. However, there are disparate views on how to classify models. Goodman (1976, p 171) remarked wryly that: "Few terms are used in popular and scientific discourse more promiscuously than 'model'. A model is...almost anything from a naked blonde to a quadratic equation – and many bear to what it models almost any relation of symbolization." Goodman recommended that the term model be used more sparingly, and:

> "reserved for cases where the symbol is neither an instance nor a verbal or mathematical description: the ship model, the miniature bulldozer, a campus, or a car; and none is a description in ordinary or mathematical language. Unlike samples, these models are denotative; unlike descriptions, they are nonverbal." (Goodman, 1976, p.172)

For Goodman, (1976, p.171) "what matters with a diagram, as with the face of an instrument, is how we read it," not "the mere presence or absence of letters or figures." He emphases that:

> "the significant distinction between the digital or notational and the non-notational, including the analog turns not upon some loose notion of analogy or resemblance but upon the grounded technical requirements for a notational language." (ibid.)

Giere (1998, pp54-56) emphases the non-linguistic character of models, but (unlike Goodman) holds that: "The term 'model' may be used for all types of representation from the initial, tentative construals of data to the well-articulated, unambiguous hypothesis or theory." This leads Giere to conclude that, "theory construction in science is models 'almost all the way up' from the phenomenology, and theory evaluation is 'models almost all the way down'." (ibid.)

According to Mike Gorman (1998) a mental model can be viewed as a kind of frame: "but one that is more visual and kinesthetic than other more prepositional types of frame." For example, Gorman (1998, p122) notes that, "Dog...is more than an abstract concept; most of us have a visual mental model of a dog, perhaps based on our favourite dog." Gorman explains that as frames can be nested within frames, mental models can be nested within mental models. Thus, "An inventor can have a mental model of an overall system, and also a mental model of how a part of a system might work." (Gorman, 1998, p.123). Gorman also uses the term mental model "to designate both individual and shared representations that are partly tacit and typically have visual and/or kinaesthetic components." (Gorman, 2005, p.293).

It is worth noting that there may be a distinction on a cognitive level between creating and using models. Bailer-Jones (1999, p.36) notes that: "Both *creating* and *using* a model are processes involving cognition, but not necessarily in the same way, and having a *picture* of a model may be crucial to *using* it." Clement's (1982, 1983, 1991) investigations on imagistic simulation in scientific model construction reveal that contemporary physicists frequently use informal, qualitative logic (including analogy and limiting case analysis) to solve problems. Clement's findings suggest that: "the transfer of runnability achieved by grounding a new model in a runnable prior knowledge schema as a source analogue may foster a type of model flexibility that aids the use of the model in transfer problems. Model flexibility would seem to be a very important feature of scientific knowledge for both experts and students." (Clement, 2003, p.4).

Thus, although numerous researchers have highlighted the importance of model creation and use in science in recent years,[18] there are **no broad-ranging, quantitative accounts of the extent to which scientists in different fields use models** (e.g. analogical or computational) and few detailed accounts of how scientists create models (whether digital, analog or a mixture of digital and analog). As Morgan and Morrison (1999, p.12-13) remark: "We are given definitions of models, but remarkably few accounts of how they are constructed." Mary Hesse's (1966) account of models and analogies, Nancy Cartwright's

[18] e.g. Campbell 1920; Braithwaite 1953, 1954; Black 1962; Hesse 1953; 1966; 1974; Harré, R., 1960, 1982, 1988, 1990; Kuhn, 1977; Giere, 1998; Gooding, 1981, 1986, 1990, 1992; Goodman, 1976; Gorman, 1998, 2005; Morrison, 1998; Morgan & Morrison, 1999; Cartright, 1983, 1999;

(1983) 'simulacrum' account,[19] David Gooding's (1990) 'construals' account, and Morgan and Morrison's (1999) 'models as mediators' account are exceptions.

According to Morrrison (1999, p.43, 44) "...many models are constructed in a rather piecemeal way making use of different theoretical concepts in nothing like a systematic process." Although models may be <u>constructed</u> in a piecemeal way, they may be <u>used</u> as structured problem-solving methods. They provide conceptual frameworks around which to build theories, and simplifying lenses through which to view complex data. Harré (1970, p.40) argues that "making models *for* unknown mechanisms" is the creative process in science and the catalyst for scientific advances. He contrasts this with "making of models *of* known things and processes" which has in his view "a more heuristic value".

One may obtain a mathematical representaion of a process, system or object in a number of ways, including *empirical modelling* and *physical modelling.* Practicing engineers, Bissel and Dillon describe *empirical modelling* as: "any technique for deriving a mathematical model with little or no underlying theory or assumptions about the object being modelled." (ibid. p.5) By their definition, *physical modelling* on the other hand, "involves using the assumptions and implications of some scientific or other law...to derive a mathematical model expressed in terms of physical variables such as mass, friction, voltage, current, etc..." (ibid.p 5). Physical modelling often involves the *process* of *simplification by abstraction*: the sophistication of models can be gradually increased as fewer phenomena are neglected, e.g. first neglect friction, then include viscous friction, then static friction.

Bissell & Dillon also describe a third approach called *system identification*, which they say is, "much less widely known outside engineering circles." (Ibid. p.5) They explain that:

> "in this approach, the system under consideration is treated as a 'black box'. A model is derived by means of input-output testing (impulse or step response, frequency response, I/O correlation with random input). Typically, system identificaiton operates with a restricted range of useful model types (often linear differential equations) and, most importantly, it delivers no model of individual *component* behaviour." (ibid. p.5)

But one could ask Bissel and Dillon, in what sense is an input-output model a model if it only replicates behaviour? As you will see in section 4.6.4, many questionnaire respondents (practicing physicists) cautioned against treating computer simulations as 'black boxes' –

[19] "[Cartwright] suggests that models are made by fitting together prepared descriptions from the empirical domain with a mathematical representation coming from the theory. (1983)" (Morrison & Morgan, 1999, p. 12-13)

where the user has no firm understanding of the theory underlying the computer model. They said that no real insights can be obtained if computer models are used in this manner. However, as shown in section 4.4, a majority of respondents believed that computer simulations have strengthened physicists visualization capabilities both in their own research area and in physics in general. I will now set the scene for this research question.

1.10 Can computer models strengthen physicists' visualization capabilities?

Dennett (1990) asked if we might:

> "make a computer that expanded our capacity to think in much the same way microscopes, telescopes, microphones and cameras have expanded our sensory capacities…Is there some way of attaching a computer to a human mind so that the mind's powers of conception are enhanced?" (Dennett,1990, pps. 299-300)

Mathematician and educator, Walter Whitely (1992) believes that computer software packages (e.g. Cabri Geometrie, Geometers SketckPad, and Cinderella.) have important functions as educational tools, saying that:

> "New computer tools, play with objects and images, and guided practice can change how students 'see' both external visuals and images in their mind's eye. The shift from simple images to insight is not a matter of luck it is a matter of learning…." (Whitely, 1992, web PDF, p.3)

Computer scientist and educational psychologist Barbara White (1993) also believes that computer simulations have their place in the classroom. Her **ThinkerTools** Research group's **ThinkerTools Force-and-Motion** software "provides interactive simulations of force-and-motion phenomena. Students can experiment with and modify the simulations in various ways, so that they develop and investigate alternative models of force and motion." [20]

Thus, another aim of this project is to enquire into the creation and particularly the use of computer simulations as visualisation tools when conceptualising and communicating physics. As we saw in section 1.9, models can be empirical, physical or mathematical. They can be used to simplify complex systems, generate a range of input-output data, produce idealized plots and graphs of the time evolution of systems, etc. According to Wisberg (1999, p.264), "visualisation plays a crucial role in sanctioning as well as in analysing simulation

[20] Quoted from the ThinkerTools website. The ThinkerTools Force-and-Motion software can be downloaded from theis website: http://thinkertools.soe.berkeley.edu/Pages/force.html

results. Not only does the epistemology of simulation call upon resources that are empirical, and come from outside of the theory, it also calls upon the faculties of the observer."

I investigate **physicists' use of computer simulations to bridge conceptual divides between different modes of thought** via a large-scale survey, follow-up e-mail correspondence and an interview with Prof. Berry. In sections 3.6 and 4.5.1 I show that experimentalists sometimes make use of simulations to help them visualise equations into their physical meaning, because abstract mathematical forms are often presented by theoreticians in their published work while physical and pictorial forms are often preferred by experimentalists.

As indicated by the work of Winsberg (1999) and Hughes (1999) the advent of the computer has changed not just the way individual problems are addressed but also the sort of enterprise in which theorists engage, and hence the kind of theory they propose. Again I use a large-scale survey and follow-up e-mail correspondence to enquire into **the advantages and disadvantages of operating in a virtual laboratory**. For example, in sections 4.5.1 to 4.5.4 I show that, among other things, computer simulations allow physicists to visualise extremely complex geometries and conduct experiments on astronomical scales (e.g. simulating the behaviour of colliding galaxies). However, I also show that many respondents emphasise that real world experimental checks should always be carried out where possible to ensure that physicists do not become disembodied experimenters. What are the other contexts in which computer simulations are useful? For example, do physicists use of computer simulations as marketing tools – to make their work look enticing, with a view to publishing in prestigious journals and obtaining funding? My survey data and interview material will explore this research question and conclude that many physicists employ computer simulations to good effect as marketing devices. In the following sections I return to the role of analogy in conceptualisation, drawing on literature in the fields of cognitive science and design studies.

1.11 Goel's thesis that it is often necessary for thoughts to be imprecise & fluid may suggest a cognitive role for playful analogies in conceptualisation.

An excellent over-view of thirty years of cognitive psychology literature can be found in Goel's **Sketches of Thought** (1995). Goel reports that: "[d[esigners are certain that there are important differences in their various systems of representation and that these differences affect their thought processes." (1995, p135). As discussed in chapters 5 and 6, my initial findings suggest that physicists also use various systems of representation in the course of problem structuring, problem solving, disseminating results and popularising physics and suggest that these systems of representation may affect their thought processes. Individuals may use any number of different contrasting or complimentary cognitive approaches in the course of problem structuring, problem solving, disseminating results, etc. According to Goel (1995, p.127):

> "Each of these observations is common knowledge among designers (Albarn and Smith, 1977; Crowe and Laseau, 1984; Goldschmidt, 1991; in press; Laseau, 1989). Unfortunately, most members of the cognitive science community have been raised in a primarily linguistic tradition and find such ideas foreign."

So, how should one investigate images, visualizations, analogies etc. when faced with a linguistically orientated research field? This was a recurring issue throughout this project. It is addressed in chapter 2, under the methodological approach taken when constructing a cognitive style framework for my case-study on Dr. Lawson. There are three main facets to Goel's thesis:

i. it is often necessary for thoughts to be imprecise, ambiguous, fluid, amorphous, indeterminate, etc;
ii. a close relationship exists between the structure of our thoughts & the structure of our symbol systems;
iii. any system of internal representation must have the properties necessary to accommodate imprecise, ambiguous, fluid, amorphous, indeterminate thoughts.[21]

I explore the first facet of Goel's thesis in my research into physicists' views on the use of analogies to conceptualise and communicate physics. As we saw in section 1.9, models and analogies are used by physicists to refine and make initial ideas more precise. In chapters 5 and 6 I will provide examples of analogies used by physicists and show that the forms of analogies they use to conceptualise and communicate physics vary according to their goals, the expertise of their audience, the tone of the discussion etc. In particular I will show that playful analogies do have an important function both in private conceptualisation and when promoting physics. I should stress that my main aims are to explicate the representational practices employed by physicists in conceptualisation and communication, and more specifically to investigate the different forms of analogy employed by physicists in different

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[21] Goel's "intuitions and sympathies are clearly in line with the train of thought stemming from Pierce, Cassirer, Langer, through to Goodman, which recognizes both the importance of symbolic activity and the multiplicity of symbol systems." ibid, p.16

contexts. My aim is not to uncover the cognitive architecture underlying problem-solving (and by extension representational) processes. I will leave that to cognitive scientists. To investigate the different forms of analogy employed in different contexts it is necessary to review the literature to explore the various ways in which analogies have been classified by others, in particularly, cognitive scientists. I shall do this in section 1.12.

1.12 How is analogy classified? A Cognitive Science Perspective

Research by cognitive scientists over the past 20 years has resulted in several detailed accounts of the cognitive processes involved in analogical reasoning. On most cognitive science accounts, drawing an analogy means identifying structural relations between the source domain and the target domain. It has been shown that by mapping concepts from a source domain (an area which is well understood) to a target domain (an area which is not well understood) some scientists use analogy to construct a model or framework within which to explore, discover, develop, and explain a new topic (cf. Holyoak, K.J., & Thagard, P., 1995; Gentner, 1983, 1989).

Kevin Dunbar (2001) has carried out extensive research on analogical reasoning among biologists, using what he dubs *"InVivo"* and *"InVitro"* methodologies. InVivo research is carried out in naturalistic settings, where groups of biologists are observed at laboratory meetings. The findings from InVivo studies can then be fed into InVitro research, which involves controlled experiments in a psychology laboratory. Dunbar's findings led him to conclude that analogy is common; often based on deep structural features and higher order relations; goal-orientated; used by scientists as scaffolding, and often discarded and forgotten after it has served as a bridge when building new explanations and models. (Dunbar, 1999, p.89) Dunbar's studies also showed that the greater the *knowledge-base* of the team, the greater the number of analogies that were generated, with experts employing more and better analogies than their less expert colleagues. Dunbar (1999) classified analogies as *local, regional* and *long-distance*, and found that the scientists' goals when they made these analogies could be grouped into four classes: (i) formulate an hypothesis, (i) design an experiment; (iii) fix an experiment; (iv) explain a result. I have summarised Dunbar's (1999) findings in table 1.0 on the next page.

Goal of biologist	Type of Analogy	Definition of type	Example	As a % of total no. of analogies used.
To design and fix an experiment	Local	where researchers make an analogy to an experiment in a very similar research area, or to a similar technique or protocol	Drawing an analogy from one gene on the HIV (virus) to another gene on the HIV (virus).	~ 45%
To formulate an hypothesis	Regional	where researchers map over entire systems of relationships from one domain to another	Drawing an analogy from the Ebola virus to the HIV virus.	~ 50%
To explain concepts to others, rather than as a source of novel hypotheses and experiments.	Long-Distance	where researchers map a concept from a very different domain to the domain they are working on	Attempting to explain the way a vacuole works by drawing an analogy to the pop song 'Hotel California'. You can check in but you can't check out.	~ 2%

Table 1.1: Summary of Dunbar's (1999) findings on the forms of analogies used by biologists in different contexts.

As you can see from table 1.1 above, long-distance analogies accounted for just 2% of the total number of analogies used. Are Dunbar's findings on this issue transferable to physicists? Cornelis' studies of analogical reasoning in modern cosmological thinking: "suggests that interdisciplinary analogies are problem-solvers, while intradisciplinary analogies generate corollaries." (Cornelis, 2000, p.179).[22] On an **inter**disciplinary level, Cornelis (2000) describes how physicist Roger Penrose drew a visual analogy to work by the graphic artist Maur Escher. Specifically, Penrose drew a "visual analogy between the graphical covering of the plane and five fold symmetrical covering of a plane with a network of electrons." (ibid. p.177). On an **intra**disciplinary level, Cornelis (2000) shows that analogies drawn between the related disciplines of astrophysics and cosmology, concerning the origin of the universe, helped to form the singularity theorem (i.e. like a black hole, the early universe contained a point of singularity). Cornelis also distinguishes between formal and informal analogies, saying:

[22] A corollary is a proposition that can be deduced easily from another proposition or theorem.

> "Informal analogies are analogies where there is a certain relation between the objects of two theories A and B, and where theory B is based on theory A by means of that relation. Formal analogies regard the relation between the methodologies of theories A and B." (Cornelis, 2000, p.165)

Cornelis suggests that if informal analogies concern a related problem, "the solution they lead to is in effect the same", while formal analogies "do not necessarily lead to rigid connections: the structure of the drawing can not necessarily have anything to do with the structure of the universe..." (p.178)

Dunbar (1999) and Cornelis (2000) both show that analogies can be used to solve problems (design and fix experiments and formulate hypotheses) by transferring methodological approaches or comparing relational features between theories. However, the distinctive role Cornelis (2000) suggests for inter-disciplinary analogies as problem solvers and intra-disciplinary analogies as corollary generators in physics does not seem obvious in Dunbar's (1999) studies in the field of biology. I shall compare and contrast the findings of Cornelis (2000) and Dunbar (1999) with the data I gather via the survey, e-mail exchanges, interview, and case study.

I shall follow Gentner's thesis in holding that drawing an analogy in science means identifying structural relations and mapping elements between the source and target domains. Gentner's (1989) **structure mapping theory** asserts that there are three main stages to analogy processing:

1) accessing the source domain;
2) performing the source to target mapping;

   (2a) judging the soundness of the match: **structural consistency**, i.e. that there is a 1:1 match between elements in the source and target; **parallel connectivity,** i.e. arguments of matching predicates must themselves be able to be placed in correspondence; **systematicity,** i.e. alignments that form deeply interconnected structures, in which higher order relations constrain lower order relations, are preferred over less systematic sets of commonalities.

   (2b) storing inferences in the target domain;

3) extracting the common principle. [23]

On my view, analogies can range from those with low level isomorphism[24] or systematicity [25] to analogies having high level isomorphism or systematicity. [26] This interpretation, common

[23] For a concise overview of Gentner's structure mapping theory, see Palmer, 1989

among 20th century cognitive scientists, was actually foreshadowed by the 19th century mathematical physicist J.C. Maxwell. On Maxwell's definition, scientific metaphor or physical analogy were where, "each term in its metaphorical [or analogical] use retains all the formal relations to the other terms of the system which it had in its original use." (Maxwell, 1890, p.227)

It is important to note that analogies can be expressed physically, pictorially and/or mathematically. For example, the analogy between the flow of heat and the flow of electric charge can be visualized as incompressible fluids flowing within channels or mathematically expressed as:

Flow of heat : $\mathbf{dH/dt = - K(T_2 - T_1)}$ is analogous to the

Flow of electric charge: $\mathbf{dQ/dt = - G(V_2 - V_1)}$ where:

H, the quantity of heat is analogous to **Q**, the electric charge;

K, thermal conductance of the rod is analogous to **G**, conductance of the wire.

T, temperature is analogous to **V**, voltage;

The analogy between the flow of heat and the flow of electric charge was put forward by William Thompson (A.K.A. Lord Kelvin) in 1842. His contemporary, J.C. Maxwell, drew on it,[27] and also on Faraday's geometrical intuitions regarding "lines of force," in formulating his groundbreaking work on electromagnetism. Maxwell took Kelvin's analogy between the flow of heat and the flow of electric charge, but in the place of heat, Maxwell imagined a continuous, incompressible, steady-flowing fluid. The properties of this fluid could thus be expressed with standard hydrodynamic equations. In the space between Faraday's Lines of Force Maxwell imagined this incompressible fluid, positing that it would flow along the same lines as Faraday's lines of force, from source (positive charges) to sink (negative charges). According to Christopher Haley (2002):

> "In terms of the history of the field, this paper [*On Physical Lines of Force*] was a very significant step, since it brought Faraday's physical, geometrical conceptions under the

[24] (derived from the Greek word 'isos' meaning 'equal' and 'morphe' meaning shape)

[25] (i.e. the analogies break down if taken beyond surface similarity because the 1:1 correspondence does not hold for a hierarchy of relations)

[26] (i.e. the analogies hold for a hierarchy of relations, from the physical picture attached to the phenomena to mathematical formalism which underlies the system)

[27] In a letter of 1854, Maxwell told Kelvin that he had been 'greatly aided' by the abovementioned analogy (cf: Harman,1990, p.234). Also, in an 1872 review of Kelvin, Maxwell underscores the value of Kelvin's 1842 paper containing the said analogy (cf: Niven, 1890, pp. 301-307). In fact, in his **Treatise** (volume 1, p. x) Maxwell pays tribute to "Sir William Thomson, to whose advice and assistance, as well as to his published papers, I owe most of what I have learned on the subject."
See also Haley (2002, web ref.)

> control of powerful analytical mathematics. Moreover, as with Stokes' hydrodynamics, the fact that the medium was treated as continuous was important for the application of advanced calculus." (Haley, 2005, web ref.).

Haley goes on to say that:

> "In terms of our understanding of Maxwell's methodology, the paper is also highly significant, since it displays a characteristic and conscious use of what Maxwell called **physical analogy:** a compromise between physical hypothesis, which he felt restricted and channel one's thinking, and pure mathematics, which sometimes lacked sufficient connection with the phenomena under discussion." (ibid.)

Maxwell thus used rigorous mathematical analysis and physical analogies to give fine-grained and coarse-grained views of phenomena, thereby extending his knowledge.

1.13 How Are Analogy, Simile and Metaphor Related?

The historical distinction between "scientific metaphor" and "physical analogy" is not clear-cut. Maxwell appears to use the terms "physical analogy" and "scientific metaphor" interchangeably. He defines Scientific Metaphor as: "the figure of speech or of thought by which we transfer the language and ideas of a familiar science to one which we are less acquainted." (1890, p.227). For example, he says:

> "the words Velocity, Momentum, Force &c. have acquired certain precise meanings in Elementary Dynamics. They are also employed in the Dynamics of a Connected System in a sense which, though perfectly analogous to the elementary sense, is wider and more general...The characteristic of a truly scientific system of metaphors is that each term in its metaphorical use retains all the formal relations to the other terms of the system which it had in its original use. The method is then truly scientific – that is, not only a legitimate product of science, but capable of generating science in its turn." (ibid.)

In my pilot studies I found that contemporary physicists tended to regard the use of **analogy** as more scientific than the use of **metaphor.** The latter they associated with poetry and popularizations of science. Thus, as discussed in chapter two, I avoided using the term metaphor when gathering data via the large-scale survey, e-mail exchanges, interviews and case study and confined my research to the study of analogy. However, I believe it is worth mentioning how analogy, simile and metaphor are related.

Broadly speaking, analogy, simile and metaphor could be said to come from the same 'species' but all three differ in subtle ways. In his paper on models and metaphors, Max Black (1962, p. 37) remarks that: "It would be more illuminating in some of these cases to say that the metaphor creates the similarity than to say that it formulates some similarity antecedently existing." With *simile* we make a (like/as) comparison between two things, usually transferring certain object attributes between domains. To use the terminology of cognitive scientists, this comparison and transferral of certain object attributes involves a 'source-target mapping'. The comparison is usually limited with simile. For example, in Shakespeare's sonnet 23: "As an unperfect actor on the stage, who with his fear is put beside his part," attributes like nervousness, awkwardness, enthusiasm etc. are intended to be mapped from the source to the target domain to convey the sense that the poet is overcome with feeling and therefore unable to express himself in person. Object attributes like age, height, weight, etc. are not intended to be mapped across. With *metaphor* we say one thing *is* another (e.g. "Juliet is the sun"). This startling fusion of attributes between source and target domains creates a new perspective, allowing us to see something in a new way. With metaphor, as with simile, only certain attributes are intended to be mapped between source and target domains. In the example, "Juliet is the sun", one transfers attributes such as warmth and life-giving radiance, but not object attributes of size, shape or colour. According to Goodman (1976) "Metaphorical force requires a combination of novelty with fitness, or the odd with the obvious. The good metaphor satisfies while it startles. Metaphor is most potent when the transferred schema effects a new and notable organization rather than a mere relabeling of an old one." (p.80)

Bowdle and Gentner (2005) suggest that despite novel similes being processed more directly than novel metaphors, poets select the metaphor form over the simile form for novel figuratives, "because novel metaphors will initially give the reader pause, they should call more attention to themselves than novel similes and may therefore be taken more seriously." (p.211). They employ Gentner's (1983) *Structure Mapping Theory* to argue that: "metaphor can be seen as a species of analogy." (2005, p.196). In their view: "literal comparisons, analogies, and metaphors all rely on the same basic mechanisms, [outlined in Gentner's structure-mapping theory] with analogies and metaphors more likely to focus on relational commonalities and metaphors more likely to involve cross-domain mappings." (2005, p.197). Gentner, Bowdle, Wolff and Boronat (2001, p.240) suggest that metaphors are typically used for: "expressive-affective purposes, and analogies for explanatory-predictive purposes. But we often speak of metaphors in science, so it might be more accurate to say that *analogy* is used in explanatory-predictive contexts, while *metaphor* can be used more broadly, in either explanatory-predictive or expressive-affective contexts."[28] It may be for this reason that the physicists in my pilot study tended to prefer the use of analogy to the use of metaphor in science.

1.14 The role of analogy in science education

I believe that my research, an empirical study into practicing physicists' use of analogy to conceptualise and communicate physics, can be of interest to researchers in the field of science education. I share the views of Nersessian (1995) and Bissell & Dillon (2000) in believing that science educators should be taught about the conceptualisation and communication methods used by practicing physicists. In this way they may learn to construct a range of analogies which, when used in a more structured way, may be less likely to encourage novices to adopt naive interpretations. For example, Prof. Coleman's dazed chicken analogy (discussed in chapter 6) has many features which could be used as a template for constructing analogies for use in a science education context: it holds for a hierarchy of relations, has little literal similarity between source and target domains and therefore reduces the likelihood of taking the analogy too far, follows an easily visualised narrative, is humourous etc. I believe that a new databank of 'good' analogies, suggested by practicing physicists (with a flair for communicating to experts, intermediates and novices) would prove useful to physics educators. My research should provide a very useful foundation (conceptually and practically) for establishing such a databank in the future.

The pedagogic value of analogical reasoning seems clear: to explain the unfamiliar, in terms of the familiar. Chin and Brown's (2000) studies of science students' attempts to understand physics concepts during physics laboratory classes found that analogical reasoning constituted a key conceptualisation technique. In Chin and Brown's view, the use of analogies may have a, "concretizing role" because they can help students "construct new explanatory models with unobservable (but imageable) structures or mechanisms (Brown, 1993; Brown &

[28] "Analogy and literal similarity lie on a continuum of degree-of-attribute-overlap. In both cases, the base and target share common relational structure. If that is *all* they share, then the comparison is an analogy (assuming, of course, that the domains are concrete enough to have object descriptions). To the extent that the domains also share object descriptions, the comparison becomes one of literal similarity. Another continuum exists between analogies and relational abstractions. In both cases, a relational structure is mapped from base to target. If the base representation includes concrete objects whose individual attributes must be left behind in the mapping, the comparison is an analogy. As the object nodes of the base domain become more abstract and variable-like, the comparison becomes a relational abstraction." (Gentner, 1989, p.208)

Clement, 1989)." [29] The "concretising" facet of analogy is both a strength and weakness. To make the invisible atomic world more accessible to students, an analogy is often drawn between the solar system and the atom. Here the sun is analogous to the nucleus; the planetary orbits are analogous to the electron orbits; the force holding the planets in their obits around the sun is analogous to the force holding the electrons in their orbits around the nucleus. Although this analogy provides students with a nice mental picture of the atom, the analogy is at best severely limited and at worst dangerously misleading. One eminent physicist who contributed to my pilot study (Muldoon, 2002) said he hoped my research would "demystify such widely quoted but misleading analogies." He was keen to stress that if the atom followed the planet analogy: "The answers obtained would be all wrong. The atom would collapse under radiation, there would be an infinity of atomic structures for each element, a perturbation would change the atomic structure for good and there would be a continuous spectrum of radiation." [30] In order to 'demystify such widely quoted but misleading analogies' I would have to evaluate the benefits and risks of analogy-based teaching at secondary and tertiary levels of education. That is beyond the scope of my project. However, as discussed in chapter 9, it is something I may follow up in future, perhaps in collaboration with science educationalists.

The planetary model of the atom was used by physicists in order to fit anomalous data into a new atomic theory. It was jettisoned in the mid 1920s, when quantum mechanics began to explain atomic structure: e.g. why the atom is stable, why atoms of a particular element are all the same, why a perturbed atom returns to its initial structure, why a perturbed atom radiates in a specific way etc. Use of the planetary model of the atom in research differs markedly from its use in educational contexts. As Bailer-Jones (1999, p.36) notes: "It is one thing to think of the atom in terms of the solar system in order to develop a model of the atom,

[29] "To facilitate the generation of ideas and expand on their thinking, the students using a deep approach used strategies such as generating mental images, creating analogies, hypothesizing, constructing thought experiments and predicting possible outcomes, giving self-explanations and constructing theories, invoking personal experiences and prior knowledge and applying them to new situations, thinking of specific examples, and asking questions." In contrast, "Students using a surface approach gave explanations that were reformulations of the questions, a "black box" variety which did not refer to a mechanism, or macroscopic descriptions which referred only to what was visible. Their questions also referred to more basic factual or procedural information." (Chin & Brown, 2000, pp. 109–138, p.130 & 109)

[30] Quoting MJ, a 69 year old physicist who was instrumental in the development of the theory of quantum bremstrahlung, i.e. the radiation of a high energy intense beam of electrons against an intense beam of positrons, something essential in the working of high energy colliders which might be constructed in the future. At the time he made these comments had been retired from CERN for 4 years but remained active as a leading member of the European Physical Society.

and an entirely different thing to use the image of the solar system in order to reason about or to teach ideas about the atom." [31]

Confusion arises if one fails to appreciate that the electron orbits must be conceptualised as occurring in **phase space** and the planetary orbits in **physical space**. Thus, from a science education perspective, the usefulness of the analogy relies on students <u>first</u> grasping the concept of **phase space**. Without this underlying knowledge students are very likely to conceptualise electron orbits as existing in the same kind of **physical** space as planetary orbits. Science educationalist, Keith Taber has also drawn attention to the obvious shortcomings of the planetary model of the atom (Taber, 2001) and continues to urge caution in the use of metaphor and analogy in science education (Taber, 2005).

Misunderstandings caused by inappropriate use of analogy are often difficult to oust. For example, research by Spiro, Feltovich, Coulson, and Anderson (1989) suggests that even when disanalogies are made explicit to university students, many still hold erroneous assumptions, often misled by connotations of non-technical descriptive language. The danger with analogy is to confuse the map with the territory. Use of analogy should not be avoided; analogy has a powerful pedagogic function. What my research suggests is that educationalists may need to adopt a more deliberate, structured approach to the use of analogies, to minimise naive interpretations.

For example, science educators should make every effort to use multiple analogies (properly selected), which counteract the omissions and over-extensions of single analogies. As Midgley notes, good writers (whatever the discipline) use: "...a whole constellation of related but widely varying images, balancing them against each other and forging them into a harmony, so as eventually to convey a new and complex message." (2002, p.214). A central aim of my research is to uncover the forms of analogies used by practicing physicists in different contexts. For example, does their use of analogy differ when they are dealing with experts, intermediates and novices, in informal and formal settings? Thus, I will now discuss expert and novice use of analogy, drawing on research in history, philosophy and psychology of science.

[31] This issue is discussed further in section 1.15.

1.15 Expert and Novice Use of Analogy: The Influence of Culturally Learned Strategies on Domain Representations.

My research focuses on experts' and intermediates' use of analogy when conceptualising and communicating physics. All of my respondents have at least a degree in physics and the majority have PhDs. I have not looked at primary or secondary students use of analogy.

It is important to note that experts' use of analogy may differ sharply from novices' use of analogy. Gentner & Jeziorski's earlier studies (1989) indicated that the processes of mapping and judging soundness of analogs were heavily influenced by culturally learned strategies. With regard to the mechanisms of analogical reasoning, Gentner's (1989) studies suggested that, "access processes seem less amenable to cultural influences and training," (ibid. p230) in which case, differences between access processes of experts and novices may be the result of experts "having different domain representations (e.g. possessing relational abstractions) rather than from their having different access processes." (ibid. p.230). Gentner believes that, "The post-access processes can be influenced both by individual training and by local strategies," and suspects that "this is the area in which training in thinking skills can be of most benefit." (ibid. p.233) . There is some evidence to support Gentner's contention. For example, the work of Larkin et al (1980) suggests that scientists work on problems in a forward, abstract manner while novices work on problems in a backward, concrete manner; the findings of Chi (1992) indicates that unlike novices, experts form abstract representations based on first principles and higher order relations.

Related to the influence of individual training and local strategies on post-access processes, there is also some evidence to suggest that language and culture can influence mental representations. In the 1920s and 1930s, the Russian psychologist Lev Vygotsky (1978) speculated on the way in which sociocultural factors influence the development of higher order psychological processes. He argued that the internalization of external linguistic processes shapes cognitive development. Vygotsky's speculations are given credence by recent research by Vigliocco (in press 2005). She suggests that subtle linguistic differences (e.g. pluralisation or gender of nouns) may lead speakers of different languages to mentally represent corresponding objects in fundamentally different ways. If this is the case, one wonders if the interactions and motions of springs, electrons, stars, galaxies etc. might be visualized in different ways depending on the gender of the nouns? Vigliocco does not address this question in her research. However, Kita's (2003, web ref.) comparison of gestures produced by speakers of different languages suggests that speakers evoke different images for the same event, in a way parallel to the linguistic difference. For example, according to Kita because *manner* (e.g. rolling) and *trajectory* (e.g. downwards) are considered separately by Japanese speakers, *imagery* is also considered separately. Thus Japanese speakers verbally recounting the imagery they saw in a cartoon, where a ball rolls down a hill, will separate the motion into two components (rolling and down) in the hand gestures they use. Kita's work therefore casts some doubt on the accuracy of think aloud protocol analysis as a means of enquiring into the mental representations of Japanese or Turkish speakers where encoding of language seems to affect imagery. There is no evidence to suggest that language encoding influences the gestures of English language speakers, however it is something I considered when choosing my research methods. The language and culture issue highlights an important issue with regard to this research project: numerous factors may influence scientific thinking and uncovering these latent factors is a difficult task. Yet it is important to ask what part cognitive, social and developmental processes play in scientific thinking. I addressed this issue in my case study of Dr. Lawson. This is discussed in section 1.16 below.

1.16 What part do cognitive, social, and developmental processes play in scientific thinking?

To obtain a comprehensive picture of scientific thinking, one must consider a myriad of interacting factors: biological influences, developmental history, demographics, personality, cognitive processes, social processes, etc. For example, the **Theoretical Structural Equation Model** proposed by Feist and Gorman (1998), (represented in figure 1.1 on p.52), integrates findings from philosophy, sociology, history and psychology of science, combining and generalizing "the path analyses of Helmreich et al. (1980) and Mansfield and Busse (1981) and the structural models proposed by Feist (1993), Reynolds and Walberg (1992), and Simonton (1977b)." (Feist & Gorman, 1998, p.33). Structural equation models can be used to deal with variables which are abstract psychological concepts e.g. intelligence, attitude etc. These 'latent' variables are observed indirectly through their effects on 'manifest' variables. One-headed arrows usually represent regression relationships, while two-headed arrows represent correlational relations, i.e. shared variation not explained by the model. (cf. Rigdon, 1996,web ref.). As Feist and Gorman point out: "...scientific behaviour is like ȧny other set of complex, integrated behaviours and can be examined from each of the psychological subdisciplines." (ibid. p.35)

However, it would be unfeasible within the time and scope if this doctoral project to attempt to take all of these spheres of influence into account when looking my respondents' different modes of thought. My survey, e-mail correspondence and interviews (see chapters 3-6) relate to cognitive and social processes in science. My case-study deals with personality and developmental history as well as cognitive and social processes, because I have made an effort to understand how Dr. Lawson's research background and working environment affected the analogies he used. For example, were his education (a mechanical engineering degree during the war) and working environment (working as a physicist-engineer at the Rutherford Appleton Laboratory) significant factors in his decision to employ certain forms of analogy in certain contexts?

Gruber (1994) also emphasises the importance of considering **context** when investigating the forms of analogy (or metaphor) used by scientists, saying that: "in scrutinizing an ensemble of metaphors, then, it is crucial to ask constantly, how does this metaphor work in this particular belief system? Merely categorizing metaphors and other figures of thought by form or by content is not enough." Following Gruber & Wallace's (1978, p.35) approach, I asked scientists what they **do** in their work. Gruber (1980) identifies several important features of scientific work, which I have drawn on in formulating a theoretical and methodological framework. In particular, Gruber (1980, p.292) defines "networks of enterprise" as being where "new lines of endeavour are differentiated, lines converge; parallels are recognized and fruitful cross-fertilizations occur; the individual responds to problems sensed in the world around him by undertaking new enterprises." I found this to be a useful concept when exploring the research path which Dr. Lawson followed (see chapter 7).

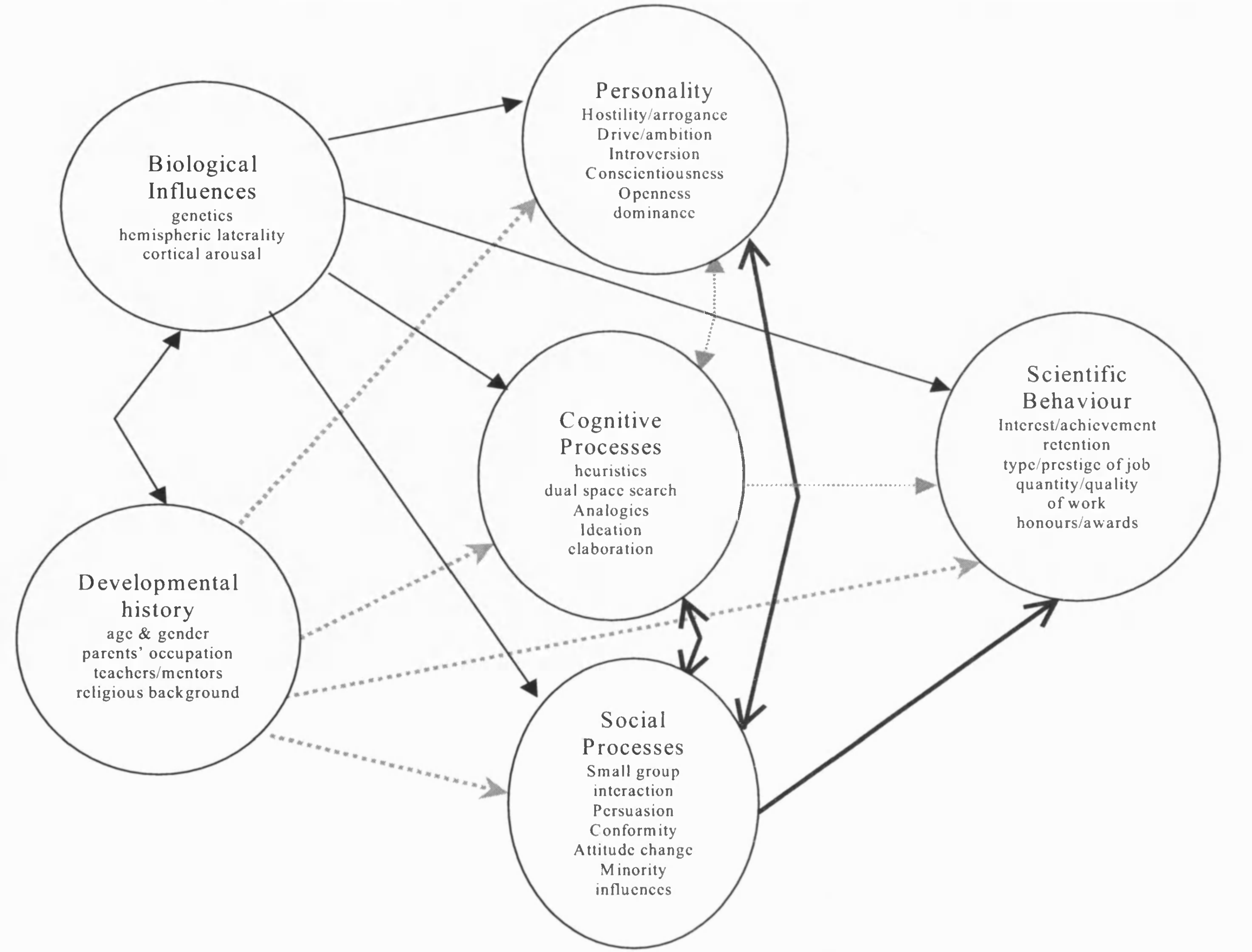

Figure1.1: A re-presentation of Feist and Gorman's Theoretical Structural Equation Model. The model is intended to imply "temporal precedence and purported causal influence." (Feist & Gorman, 1998, p.33). For example, Feist and Gorman propose that *biological* and *developmental* characteristics are the first structures to develop and have direct influences on *personality, cognitive* and *social processes*, and significant indirect influences on *scientific behaviour*; the most direct influences on scientific behaviour are caused by *personality*, and *cognitive* and *social processes*.

1.17 Cognitive Style: Different Strokes for Different Folks

Cognitive style has been defined as "an individual's preferred and habitual approach to organising and representing information." (Riding & Rayner, 1998, p.8). Riding & Cheema (1991) and Riding & Rayner (1998) have identified two principal cognitive style dimensions:

(a) The *Wholist-Analytic Style* dimension of whether an individual tends to *organise* information into wholes or parts;

(b) The *Verbal-Imagery Style* dimension of whether an individual is inclined to *represent* information during thinking verbally or in mental pictures.

On this view, individuals are positioned along continua, with a ratio indicating their position on a dimension.

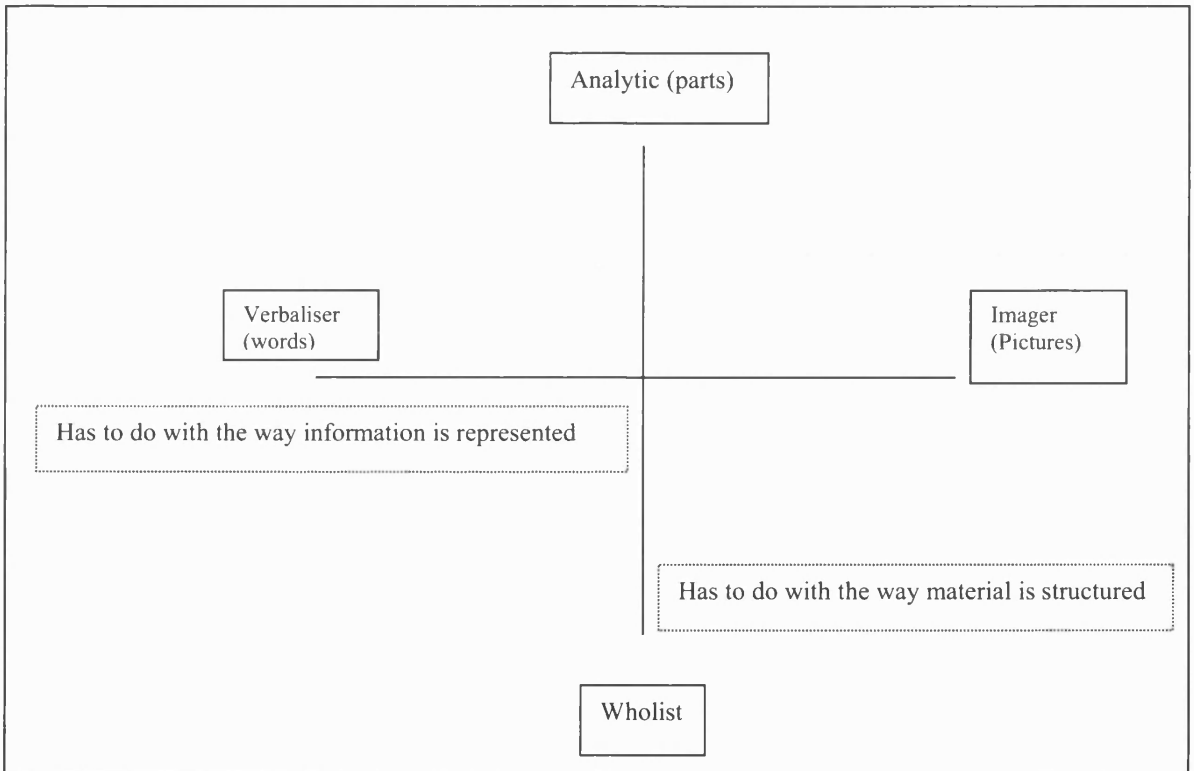

Figure 1.2: A representation of Riding's (2001) Cognitive Style Dimensions diagram. It positions individuals along continua and assigns them a ratio to indicate their position on a C.S. dimension.

Thus, for example, while I often compartmentalise things into discrete parts for individual analysis, I also like to see the 'big picture': to visualise how these discrete parts relate to each other, by sketching it (graphically) or by drawing up an overview (textually). I would therefore position myself near the "Wholist" end of the continuum and near the "Imager" end of the continuum.

As will be discussed in chapter 2, I used the *Cognitive Styles Dimension* as an initial guide when analysing and theorising about my case study material. I did not choose to locate my subject within this space because there are some limitations to the *Cognitive Styles Dimension* system of classification. For example, one could ask where diagrams, schematics, sketches, mathematical equations, geometrical proofs, physical models, and computer models fit in this scheme? Goodman (1976) articulates what many historical and cognitive case studies show - that there are severe problems inherent with classifying symbol systems as 'linguistic' or 'pictorial', 'sentential' or 'diagrammatic', 'proposition based' or 'image based' etc.

Goodman (1974) offers a rigorous (but rather complex) system for classifying representations, according to his theory of *notationality*, *density*, *modes of reference*, and *repleteness*. On Goodman's view, a scheme is *dense* if it "provides for the infinitely many characters so ordered that between each two there is a third." (Goodman, 1976, p.136). A scheme is *replete* if little can be ruled out, and *attenuated* if certain things can be ruled out. As mentioned in section 1.9. Goodman stresses that: "The mere presence or absence of letters or figures does not make the difference. What matters with a diagram, as with the face of an instrument, is how we are to read it." (1976, p.171) Goel's exploration of the cognitive processes involved in *Design Problem Solving* also attest to the shortcomings of the form of classification used in the *Cognitive Styles Dimension.*

It is especially important to note that an individual actively varies these parameters in the creative *process*. As Gruber (1995, pp. 410 & 411) puts it:

> "Thinking moves from one modality to another, from visual images to sketches, to words and equations explaining (i.e. conveying the same meaning as) the visualization. The thinker is pleased to discover that certain structures remain invariant under these transformations: These are his ideas. Dialogues, both internal and external, is a ubiquitous part of the process."

For example, as discussed in section 1.14, Maxwell drew on Kelvin's physical analogy between the flow of heat and the flow of electric charge, and on Faraday's geometrical intuitions regarding 'lines of force', and then expanded on and refined these conceptualisations through the use of contimuum mechanics – a powerful analytical method with which Maxwell was particularly skilled. Thus, Maxwell moved between several modes of thought when building his theory. He used physical and pictorial analogies e.g. of vortex currents, which he expressed through sketches and also abstract mathematical equations. One could say that one reason why analogies are useful is that they contain deep structural relations which hold between analogous systems, i.e. they contain certain 'invariants'.

Thus, I have used some particularly relevant studies regarding cognitive style to inform my research design, in particular in my case study, when constructing interview questions and analysing the resultant comments. However, as I emphasise in the next chapter, I have not attempted to classify my respondents according to any particular cognitive style. The theoretical framework on cognitive style was a useful map with which to navigate certain territories but, because of its limitations, I did not follow it closely.

1.18 Knowledge Gap in Literature and Summary Of Research Questions

My literature review has identified some key knowledge gaps in the literature. I have grouped them into four sets of research questions. The first three groups of research questions are investigated via the on-line questionnaire, the follow-up e-mail exchanges with a select sample of questionnaire respondents, and the semi-structured interview with Prof. Berry. The fourth set of research questions explores in more detail many of the questions contained in groups 1, 2 and 3. It is specific to my case study of Dr. John Lawson.

Group 1: Visualization.

Firstly, on the topic of **visualization**, I have found no broad-ranging, quantitative accounts concerning the extent to which practicing physicists experience difficulties getting a mental picture of the physical processes in their research and few accounts of how they overcome any difficulties they have. The historical case studies of Clement, Gooding, Gorman, Gruber, and Miller provide remarkable depth but not breath. Thus, the on-line questionnaire and follow-up e-mail exchanges will address the following research questions:

- *To what extent do a sample of physicists experience difficulties getting a mental picture of the physical processes involved in their research?*
- *What reasons do they give for having/not having these difficulties?*
- *Where physicists do have difficulty visualizing the physical processes involved in their research, how do they overcome this?*

Group 2: Computer Simulations as Visualization Tools.

The second group of research questions will deal with physicists' use of **computer simulations** as visualization tools. Using the same data gathering means as in group 1, I will investigate the following research questions:

- *To what extent do these physicists employ* ***computer simulations*** *in their research?*

Again, although Morgan and Morrison (1999), Hughes (1999), Winsberg (1999) et al discuss the use of computer simulations in science, there are no large-scale surveys to indicate the extent to which physicists based within certain research areas use computer simulations as visualisation tools.

- *In what* ***contexts*** *do these physicists employ computer simulations?*

This will be deduced from the examples provided by respondents in response to Q4b of the on-line questionnaire. The aim is to produce a range of contexts in which physicists find computer simulations useful. By cross-referencing the examples provided by respondents with the research backgrounds of respondents one may be able to see that researchers in certain fields tend to use computer simulations for specific things, e.g. visualising complex geometries, the time evolution of complex systems, designing and building equipment etc.

- *What reasons do these physicists provide for not using computer simulations in their research?*

This research question will show whether respondents are not using computer simulations as visualisation tools because they do not need them in this context, or whether respondents are wary of using computer simulations as visualisation tools for some specific reason.

- *Do these physicists believe that computer simulations have strengthened physicists' visualization capabilities (a) in their own research area? (b) in physics in general?*

Walter Whiteley (1992, web ref) highlights the importance of teaching students to see like a mathematician and underscores the value of computer software packages. According to Chandrasekran & Narayanan (1992, p.30): "Prior exposure [to diagrams and other kinds of images] can lead to perceptual fluency in recognition and classification." Thus, it will be interesting to see if practicing physicists believe that computer simulations have strengthened physicists' visualisation capabilities in their own research area and in physics in general. This will be ascertained through a quantitative and qualitative question in the on-line questionnaire. I expect a range of comments from the positive end of the scale to the negative end of the scale.

- *What do these physicists believe are the possible* ***disadvantages*** *of employing computer simulations in research?*

It is possible that respondents may not have made comments on the negative end of the scale in the previous question, thus this question will ask practicing physicists to consider the possible disadvantages of computer simulations. It will be interesting to see if any common themes emerge and if they are in any way related to the branch of physics within which respondents work.

- *Can computer simulations provide physicists with* ***insights*** *when conceptualising and communicating physics?*

This question arose from the comments of questionnaire respondents. It was addressed in my semi-structured interview with Prof. Berry – a theoretical physicists who uses computer simulations regularly in his work in quantum physics.

Group 3: Analogy

The third group of research questions will focus on physicists' use of **analogy** to conceptualise and communicate physics. Using the large-scale on-line survey and follow-up e-mail exchanges with a select sample of these respondents, I will explore the following research questions:

- *To what extent these physicists employ analogy in their research?*

- *What reasons do these physicists give for not employing analogy in their research?*

  This question will highlight the limitations of analogical reasoning. This will be relevant to the use of analogy within the context of science education.

- *To what extent do these physicists generate* ***original*** *analogies in their research?*

  This is an extremely novel research question that has not, to my knowledge, been investigated by others.

- *To what extent do physicists use analogy when communicating with different audiences?*

This research question will explore whether analogy is used less with experts than with novices; and less during formal discussions than informal discussions. It will combine quantitative responses (selections from a 7-point scale) and qualitative responses (written comments where elaboration is asked for) thereby providing a rich set of data which can be re-coded for particular themes e.g. respondents may say that they still employ analogy to the same extent with experts as with novices, but the analogies become more complex and abstract.

- *What forms of analogy do they use in different contexts?*

- *What are the characteristics of a good analogy?*

As a theoretical framework, I will draw on Gentner's (1989) Structure Mapping Theory of analogy, Dunbar's (1999) studies of biologists' use of analogy in their research and Cornelis's (2000) studies of cosmologists' use of inter- and intra-disciplinary analogies.

Group 4: Case Study exploring in greater depth key questions from Groups 1-3.

I used the findings of the large-scale survey to guide my case-study investigations. I addressed the following research questions:

- *To what extent did the case study respondent (Dr. Lawson) experience difficulties getting a mental picture of the physical processes in his research?*

- *What reasons were given by Dr. Lawson for having/not having difficulty?*

- *How did educational, professional, cultural, historical, etc. aspects impact on Dr. Lawson's approach to problem solving?*

- *To what extent did Dr. Lawson use analogy to acquire and promote insight?*

This question arose early in my analysis of Dr. Lawson's work as he frequently mentioned the use of analogy as a means of gaining insights.

- *How does* ***physical*** *insight differ from* ***pictorial*** *insight in Dr. Lawson's view?*

This distinction between physical and pictorial insight arose from analysis of Dr. Lawson's scientific papers and book, because he uses these terms frequently throughout.

- *To what extent did Dr. Lawson use analogy to bridge sub-disciplinary boundaries?*

In a 1971 paper, Dr. Lawson remarked that "... languages and notations differ; people brought up in plasma physics, microwave tube and accelerator environments tend to use different descriptions and different groupings of fundamental constants...and we suffer from the same problems that trouble the workers on that notoriously unsuccessful project, the tower of Babel." [32] In a subsequent interview I asked Dr. Lawson about this issue and he remarked that he used to regard himself as a 'translator' between these sub-disciplines. This lead me to investigate the techniques he used in this capacity and to discover that he employed analogy and synthesis as translation devices.

- *What types of analogies did Dr. Lawson employ in this context? I.e. were they within domain or between mappings, physical, pictorial, mathematical etc.*

Using Dunbar's (1999) studies of biologists' use of analogy in their research and Cornelis's (2000) studies of cosmologists' use of inter- and intra-disciplinary analogies as useful reference points, I investigated the forms of analogy employed by Dr. Lawson in 35 of his scientific papers and in his book on the physics of charged particle beams.

In the next chapter I will discuss the way in which I went about answering these research questions. I will outline the theoretical and methodological frameworks which influenced my research design.

[32] Dr. Lawson writes on p.1 of *"Diversity and unity in sources and beams,"* published in the proceedings of a symposium on **Ion Sources and formation of Ion Beams**, held at Brookhaven in 1971.

Chapter 2

Research Design

"The dimmed outlines of phenomenal things all merge into one another unless we put on the focusing-glass of theory, and screw it up sometimes to one pitch of definition and sometimes to another, so as to see down into different depths through the great millstone of the world."

James Clerk Maxwell, "*Analogies*" (February 1856)
"*Are there Real Analogies in Nature?*"

In Campbell, L. & W. Garnett, (1882), *The Life of James Clerk Maxwell,*
London: Macmillan & Co. p.237

2.0 Theoretical and Methodological Aims

In section 1.17, I remarked that in order to obtain a comprehensive picture of scientific thinking, one must consider a range of interacting factors: biological influences, developmental history, demographics, personality, cognitive processes, social processes, etc. Fest and Gorman's (1998) *Structural Equation Model* (figure 1.1) provides a diagrammatic rationale for the need to draw on different kinds of study, each using different methods, in order to provide a fuller picture of scientific thinking. My methodological approach was influenced by the **fine-grained historical case studies** of Gooding (1990, 1992, 2005), Gorman (1990, 1992), Gruber (1980), Nersessian (1992, 1995), and Tweney (1985); the **empirical laboratory investigations** of Dunbar (1999, 2001), Gentner (1983), and Klahr (2000); the **sociological studies** of Latour (1987), Collins (1974), and Henderson (1995, 1991); the **anthropological studies** of Traweek (1988) and Forsythe (1993, 1994); and in the field of pragmatics and linguistics, Myers' (1990, 1991) **textual analyses of scientific writings**.

From my perspective, (i.e. given my timeframe, resources, expertise, etc), the abovementioned methodological approaches all possessed strengths and weaknesses. For example, although fine-grained historical case studies offer an excellent window on the cognitive processes involved in scientific reasoning, they are case-specific, not generalizable, require meticulous attention to detail, and great patience and skill in interpreting and recreating events. Well-designed empirical laboratory investigations can offer in-depth knowledge of well-structured problems in controlled environments but, as Goel (1995) points out, they rarely deal with ill-structured problems occurring in naturalistic settings. Sociological and anthropological studies are useful for unveiling the complex web of human interactions that are part of the scientific enterprise, but they are time-consuming to conduct and require special 'interactional expertise'. (Collins & Evans, 2002, p.254). Although textual analysis is an excellent means of deconstructing the written word, it is inappropriate for use with images, visualizations, pictorial analogies etc.

My aim was to see down into different depths from different perspectives and thereby avoid over-reliance on any one method. I began by constructing an appropriate theoretical lens through which to view my material then alternated from a macro to a micro level of investigation. My combined-method approach consisted of an initial global search plus content analysis of physics journals and magazines to identify the various *forms* of analogy in use;[33] a large-scale survey to gather empirical evidence from practicing physicists on issues surrounding visualization and analogy; follow-up e-mail exchanges

[33] (this pilot work is presented in my masters dissertation, Muldoon, 2002);

with 13 of these physicists in order to enquire further into individual physicists' use of analogy and computer simulations in different branches of physics; an in-depth interview with a distinguished theoretical physicist to investigate the role of computer simulations in conceptualising and communicating quantum physics; and an historical case study of the work of a prize-winning engineer-physicist, in order to understand how the atmosphere in which he worked impacted upon the *forms* of analogy he used to conceptualise and communicate physics.

One of the key strengths in the overall design of the project was that the initial discoveries from the on-line questionnaire could be taken on board and pursued further in the follow-up e-mails, the interview and the case study, and the distinctions and subtleties could be teased out. For example, one of the first issues to surface in the questionnaire data was what might be called *"meanings in flux"*. There were many different interpretations of the terms *"research"*, *"analogy"*, *"visualization"*, and *"computer simulation"* amongst respondents. Though this usually indicates inadequate operationalization [34] in the design of a questionnaire, it was in fact a conscious decision to give no definitions of these terms. The logic was that any definitions supplied in the questionnaire would be either too specific or too vague and would act as an obstacle in gathering a wide variety of examples of visualizations, computer simulations and analogies from across the physics community. Allowing physicists to interpret the terms for themselves, to discover what e.g. *"computer simulation"* means to them, may highlight trends in interpretation across the physics community. At the very least it would help me to develop a nuanced classification of the terms, by using the findings from the on-line questionnaire to inform the following three strands of research. This approach was extremely successful.

Numerous researchers have shown that the case study method can offer a 'window on cognition'. (E.g. Clement, 1991; Gooding, 1990, 1992; Gorman, 1998; Gruber & Wallace, 1978; Holmes, 1993, 2004; Nersessian, 1992; Tweney, 1985 etc.) By analysing in fine detail the work of an individual, one can begin to develop a 'theory of the individual'. My theoretical and methodological approaches, particularly in my case-study, have many features in common with Gruber's (1980) *Evolving Systems Approach,*[35] which recognises that individuals exhibit varying degrees of creativity and inventiveness; possess widely varying life histories, 'networks of enterprise', personalities, styles, work habits, etc. Gruber circumscribes the aims of his work by imposing three key restrictions:

[34] "Operationalization refers to the rules we use to link the language of theory (concepts) to the language of research (indicators)." Rose & Sullivan, 1996, p.13

[35] As Lavery (1993, p.106) notes, Grubers method has been used: "to investigate such individuals as Antoine Lavosier, William Wordsworth, Michael Faraday, William James, Vincent Van Gogh, Erasmus Darwin, George Bernard Shaw, Sigmund Freud, Dorothy Richardson, Benjamin Franklin, Albert Einstein, Anaïs Nin, and John Locke."

> "**Restriction 1:** Our aim is *not* to explain how the person became creative. Rather, we are interested in how he or she functions when being creative and how this creative process evolves over time." (Gruber, 1980, p.270)
>
> "**Restriction 2:** Our theoretical aim in this essay is *not* to use the study of extraordinary creative processes to draw any conclusions about the general population." (ibid. p.275)
>
> "**Restriction 3:** Our aim is *not* to make law-like generalizations about creativity, but to develop an evolving systems approach that will serve as a guide to the study of creative individuals." (ibid. p276)

Restrictions 1,2 & 3 also apply to this project. My aim has been to provide a detailed account of the tools, techniques and problem solving strategies employed by my case study respondent in his work; in particular the role of analogy in cognition and communication. This individual is not intended to be representative of physicists (-engineers) in general: he had an unconventional physics education (during world war 2) and spent much of his career working more or less free-lance at Harwell and the Rutherford Appleton Laboratory. This cultural and professional background mediated his experiences, shaped his career path, and affected the development of his cognitive style(s). The tools, techniques and problem solving strategies he used in his work must be situated within this cultural and professional matrix. Thus, throughout the case study, an attempt was made to follow Gruber's (1985, p.178) suggestions:

> "... To place the person in history, to describe his ensemble of metaphors [/analogies], to pay close attention to his system of categories and to changes in his units of analysis, to see each activity as part of his network of enterprises, to search out and examine those very special skills that the particular creative person may have, and to try to understand his special point of view."

Following Gruber (1985) advice, I have attempted to identify the unique characteristics of my case study subject, to uncover:

> "an organization that was concentrated by the person himself in the course of his lifetime, in the course of his work, as needed in order to meet the tasks that he encountered and that he set himself." (ibid. ,p. 177)

Employing a methodology in which the interviewee provides a personal account can produce a wealth of valuable information, but can also suffer from several kinds of error. Memory-related kinds of errors were particularly relevant to this study, as the case study respondent was an octogenarian who, though extremely cognizant, often remarked that his memory was not what it used to be. Thus, every effort was made to avoid three kinds of error which in Gruber's (1995) terminology are defined as:

> "**Telescoping:** The loss of detail due to limitations of memory, intermediate steps drop out and beginnings and ends remain." (Gruber, 1995, p. 405)
>
> "**Rationalization:** Changes in intuition and in affective feeling disappear from memory and are replaced by post hoc rational and empirical accounts." (ibid.)
>
> "**Decontextualization:** a coherent episode in which a moment (or several) of insight occurs can be thought of as a figural event seen or remembered against a background of several overlapping contexts." (ibid.)

Though they suffer from such weaknesses, retrospective accounts can be an extremely useful method of uncovering *'affective transformations'*: key events which had an impact on the individual's network of enterprise, but which are often undocumented or private. For example, in section 7.2.4 we see that the collapse of Dr. Lawson's first project, when he was in his early 20s, affected his future approach to similar projects – he became renowned as 'a good critic', able to spot potential problems before they arose. The subject's reports about himself are taken as an inevitable point of departure so, as Gruber puts it: "… we do not abandon critical judgement and reconstructive work. We have the double task of reconstructing events from the subjects point of view and then understanding them from our own." (Gruber, 1980, p.276-277). Following Gruber's approach, the aim is not to "discover anything like a 'latent structure,' a set of relationships unknown to the knower." The methodological approach used here has the intention of "schematizing the ideas of the creative thinker in a way that he would probably recognize and accept as a reasonable representation." (Gruber, 1980, p.290). With this in mind, I gave Dr. Lawson the opportunity to proof read some draft chapters in the final year of this project. He returned the draft chapters (with some minor corrections) and in the accompanying letter wrote:

> "…as far as I can tell you have given a fair and accurate account of our interviews and painted a flattering picture of me from a study of my published papers and other people's comments. Best wishes and good luck for the future." (Dr. Lawson, 01/02/2006).

I will now discuss each method in turn. First, I mention the literature review (already discussed in chapter 1). Second, I briefly outline the pilot work consisting of a global search and content analysis of physics journals and popular science magazines to explore the forms of analogy used in different contexts. Third, the survey data (i.e. gathered via an on-line questionnaire) is discussed in detail as this strand of my research accounted for over half of the data gathered. Fourth, I explain the rationale behind the selection of 30 questionnaire respondents to enquire further into the techniques they use to conceptualise and communicate physics, and outline the backgrounds of the 13 who replied to my follow-up e-mail queries. Fifth, I briefly discuss the use of an in-depth interview with Prof. Sir Michael Berry to focus on the techniques he employs to conceptualise & communicate quantum mechanics. Sixth, I provide a detailed account of my case study of a physicist-engineer who was an enthusiast for analogy and had interesting research training.

2.1 Method 1: Literature Review:

As discussed in the previous chapter, a wide-ranging literature review of scientific thinking was conducted throughout the duration of the project. This included the fields of history, philosophy, psychology, and sociology of science as well as science education, science communication, literary theory, and design studies. These explorations provided a broad perspective, theoretically and methodologically, enabling me to formulate appropriate research questions and choose a suitable methodology for this work, given the time and expertise at my disposal.

2.2 Method 2: Pilot Work:

Pilot work for this thesis was carried out in 2002 for my MSc dissertation, *"On the Role of Analogy in Physics."* This early work consisted of a global search plus content analysis (of physics journals, magazines, popular science books etc.) to identify forms of analogy used in various contexts; semi-structured interviews (with five physics lecturers based at the University of Bath); and semi-structured e-mail correspondence with seven physicists based in Ireland, France, Switzerland, the U.S., and Australia.[36] This early work informed and shaped subsequent doctoral work. Firstly, the word 'analogy' was used throughout my doctoral work as the term 'metaphor' had poetic connotations for some pilot-study respondents. Secondly, some of the examples of analogy used by the pilot-study respondents were used in the on-line questionnaire. Thirdly, the remark by an eminent pilot-study respondent from CERN that he hoped my work would, 'demystify such widely quoted but misleading analogies' as the solar system model of the atom, was an impetus to explore the differences between experts' and novices' use of analogy.

[36] Three were former physics lecturers of mine from NUI Galway, and four were physicists I had corresponded with during my internship at the **Institute of Physics**, when working on a **Physics World** magazine, special issue on **Art and Science.**

2.3 Method 3: Web Questionnaire:

There are many advantages to using a web questionnaire to gather data (from a sample of physicists): it can be distributed to very large sample, at virtually no cost, it is easy for respondents to submit data, and the incoming data (already in electronic form) can be easily imported into electronic packages (e.g. Excel & SPSS for qualitative and quantitative analysis), saving considerable time and money.

2.3.1 Designing and Broadcasting the web questionnaire.

In the winter of 2002, a web questionnaire on conceptualisation and communication in physics was designed, built and piloted on a small sample of physicists at the University of Bath. [37] Feedback from the pilot study resulted in several amendments to the questionnaire. [38] As mentioned in section 2.0, I made a conscious decision not to rigorously define terms such as 'research', 'analogy', 'visualizations' , 'computer simulations' because I wished to see how physicists from different branches of physics interpreted these terms. In order to encourage a broad interpretation of the term 'analogy', I supplied several exemplary analogies, ranging from the metaphorical end of the spectrum to the mathematical end of the spectrum. [39] Interestingly, even these examples of analogies were questioned by some of the respondents. These differences of interpretation revealed some physicists' hidden preferences for one way of reasoning and dislike for other, "simplistic", ways of reasoning.

In order to reach a good cross-section of the physics population in the UK and Ireland, the URL of the web questionnaire was broadcast by:

(i) Constructing an electronic mailing list by trawling through physics department web-pages, copying e-mail addresses of some 500 physicists from 10 universities (and observatories) in Ireland, and some 3,200 physicists from 55 universities in the UK. Though this method was time-consuming, it did provide a good cross section of the

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[37] I am grateful to Ms. Yvonne Aburrow for her infinite patience and kindness in assisting me in the construction (and repeated re-construction) of the on-line questionnaire, and also for making me more conscious of my own style of graphic design.

[38] E.g. the term "thought experiment" was replaced with the term "visualization", the questionnaire length was shortened and respondents were afforded the opportunity to download the questionnaire in MS Word format, so that they could complete it off-line and e-mail it back at their leisure. (The findings from the questions on thought experiments are outlined in section 3.7 of this thesis).

[39] "Some physicists use analogy in their research.
- e.g. using a billiard ball model when considering the movement of charge through a solid;
- e.g. comparing ultrasonic transmission down a rod, to an electrical transmission line;
- e.g. comparing the vibrations of a 'cosmic string' to the vibrations of a guitar string;
- e.g. Schrödinger's equation is derived by using Hamilton's mathematically unified treatment of geometrical optics and analytical mechanics;
- e.g. Sheldon Glashow has remarked that he 'was led to the group SU(2) x U(1) by analogy with the approximate isospin hypercharge group which characterises strong interactions'."

population of physicists (doctoral students through to deans) based in academia in Ireland and the UK.

(ii) An appeal in *Physics World* magazine *Letters to the Editor*[40]. The magazine has a circulation of approximately 20,000 people, mostly in the UK and Ireland but it also has readers in Australia, New Zealand, the USA etc. Importantly in this case, readers include many physicists who would not have been in the sample who were e-mailed directly i.e. retired physicists, physicists working in industry, and physics students at pre-doctoral level. In fact, as a result of seeing my letter to the editor of Physics World one retired physicist wrote to me about his experiences of using analogy in his work and enclosed several of his scientific papers, spanning a 40 year period. This respondent subsequently became the subject of my historical case study.

2.3.2 Categorising respondents according to research background, age, gender, occupation, etc.

In order to compare and contrast responses between sub-cultures of the physics community, and to explore whether physicists' use of analogy might be influenced by age, gender, experience, etc. the questionnaire began by asking respondents a mixture of qualitative and quantitative questions concerning their education, experience and research interests. For example:

i. What third level qualifications do you hold?

(Respondents were asked to select **Yes/No** from a drop down menu comprising: **BSc, MSc, BEng, MSc, PhD, PostDoc**[41]**, other**)

ii. In what subject area?

(Respondents were asked to fill in the empty field)

iii. With which of the following groups would you associate yourself?

(Respondents were asked to select **Yes/No** from a list of 12 physics groups[42], and also provided with the opportunity to enter an "other" option)

[40] "How do you see?" March 2003, Vol. 16, No.3, p.20

[41] With hindsight the word 'research experience' should have been added to 'PostDoc' as it is not a qualification like the others.

[42] The Institute of Physics' 12 physics groups were utilised in order to cover as broad a range as possible.

iv. What is your present job title, occupation or course of study?

(This was an open field)

v. Age

(This was an open field) [43]

vi. Gender

(This was an open field)

vii. What are your present research interests? Please include some keywords.

(This was an open field)

2.3.3 On getting a mental picture of the physical processes involved in research.

Question two of the online questionnaire posed the following question: *"Do you ever find it difficult to get a mental picture of the various kinds of physical processes involved in your research?"* As discussed in chapter 1, certain simplifying assumptions had to be made when deciding on the phrasing of the questions. I was well aware that many forms of visualizations exist, and that many physicists do not seek mental pictures of physical processes. However, I reasoned that by taking a simple approach and asking respondents if they found it difficult to get a mental picture of the various kinds of physical processes involved in their research, this would elicit a wider range of responses, i.e. from physicists for whom mental pictures were meaningful and useful, and from physicists who did not seek or use mental pictures of physical processes. As the data in section 3.2a and 3.2b shows, this approach proved successful.

[43] Some physicists included "years" in their reply, which goes to show how effective their early training was i.e. the constant reminder to always include the correct units with every calculation!

2.3.4 Receiving Responses to the on-line questionnaire:

Between February and May 2003, I received 225 questionnaire replies from physicists who had either received a direct e-mail or read my appeal in *Physics World* magazine. This represented a very low response rate, but produced a wealth of material, providing a good map of the territory, informing and shaping future investigations. [44] In his studies of biologists' use of analogy, the cognitive psychologist Kevin Dunbar (1999, p.89):

> "..found that scientists have little memory for the analogies that they use. When we go back and ask the scientists to remember how they generated a new concept or solved a problem, at a meeting that we recorded, they have little memory of how it occurred. Thus biographies and anecdotes do not mention many of the analogies that went into making a scientific theory."

I accept Dunbar's criticisms of biographical and anecdotal accounts of reasoning by analogy. However, I believed that questioning physicists on this issue and promoting them to reflect on the methods they use in their work could still prove enlightening. My findings are testimony to this.

2.3.5 Analysing Web Questionnaire Data

Questionnaire replies arrived in an electronic format not conducive to analysis. Thus, each reply was imported into an *Excel* spreadsheet, with columns representing each question and rows representing each physicist's response. Quantitative questions and responses were imported into *SPSS*. Re-coding was carried out on some of the data (e.g. defining age ranges, educational levels etc.). Some rudimentary statistical analyses were performed on these data to uncover any possible patterns. Rigorous statistical analyses were not performed because the purpose of the on-line questionnaire was not to establish statistically significant correlations and hence make law-like generalizations. The objective was to gain insight on an exploratory level, insight which could then be incorporated into in-depth, follow-up studies. Qualitative questions and responses were analysed using *Excel*. To obtain an initial, tentative hypothesis of the individual, each physicist's full set of responses was read in turn. For example, how educational background, age, research interests etc. might have affected visualization difficulties, the techniques used to overcome their visualization difficulties, views on computer simulations etc. As patterns began to emerge, all 225 responses to a given question were read and the qualitative

[44] One possible factor in the low response rate is that the University of Bath firewall blocked and/or re-directed incoming replies if they came from a domain name that the server did not recognise. Many re-directed replies were subsequently retrieved but unfortunately an unknown number of replies were lost in cyberspace.

responses of each physicist thematically colour-coded. E.g. in response to Q2c. *" Where you do have difficulty [getting a mental picture of the physical processes involved in your research], how do you overcome this?"* mention of sketching was colour coded grey, analogy was colour-coded orange, simplification/limiting case analysis was colour-coded pink, change of scenery was colour-coded green, etc. [45] In a new excel spreadsheet, each question was listed by row, and a colour-coded summary of each theme was set out in each column. A tally was made of the number of times a said category of response was mentioned, and the totals were inserted into the colour-coded summary. The categories were then ordered (left to right) according to their frequency of occurrence. For maximal visual impact, the colour-coded summary was then graphed in excel. This process was repeated for every qualitative question. This system of analysis proved useful at uncovering the key factors accounting for visualisation difficulties, the key techniques employed to overcome visualisation difficulties, the key forms of analogy employed in different contexts, the key views on computer simulations etc. They are not included here because they were intermediate tools of analysis. Re-categorisation was carried out 2 years later, after additional understanding had been gained through the follow-up e-mail correspondence, interviews and historical case study.

2.3.6 Classifying the Forms of Analogy used in Research

The 147 examples of analogies provided by respondents were categorised and then counted to explore the forms of analogy employed. Boon's (2005, p.4) system of classification for models, i.e. mechanistic, diagrammatic, nomo-mathematical was a useful framework and reference. For example, she looks at the epistemological aims of the model users, the scientific knowledge they utilise, the manner in which the models are expressed or represented, and the use for which the models are intended. This is summarised by Boon (2005, p.15) in tabular form and reproduced by me below.

[45] My colour-coding system had some logic: e.g. sketches (i.e. pencilling) = grey, change of scenery (i.e. taking a stroll in nature) = green; simple models (i.e. Barbie dolls) = pink etc. Also, when colour-coding the number of physics groups/branches with which physicists associated themselves, I used a temperature-colour gradient scale, with 'cold' colours at low numbers and 'warm' colours at high numbers. This kind of colour-coding was something I did subconsciously at first but, once I became conscious of it, I continued to employ it as it facilitated speedy visual analysis.

Table 2, page 15	diagrammatic model	nomo-mathematical model
a) Epistemological aim	Distinction in spatial regions and causal explanation of physical behaviour in each region.	Mathematical description of behaviour of the phenomenon
b) Scientific knowledge utilized	Phenomenological knowledge and/or causal understanding of the phenomenon.	Theoretical principles, theoretical and empirical laws, and knowledge presented in diagrammatic model.
c) Representative tool	Diagram or graph-like schema	Set of mathematical equations
d) Intended use	i) Explaining how phenomenon in technological device is physically produced or manipulated. ii) Basis for nomo-mathematical model.	i) Quantitative description of physical parameters and variables relevant to technological device. ii) Basis for computer simulations

Table 2.1 A re-presentation of Boon's (2005) system of classification of models

I initially believed that Boon's (2005) attention to the scientific knowledge utilised, the form of expression and the intended use would prove very useful in my endeavours to classify the 147 examples of analogy. However, as there was often very limited detail provided in each of my examples of **analogy**, it was difficult to know with certainty what kinds of models the analogies were being used in. Consequently it was difficult to closely apply Boon's (2005) system of **model** classification to the classification of my examples of **analogy.** Drawing on Gentner's (1989) structure mapping theory and on b), c) and d) of Boon's system of classification, I therefore classified my sample of analogies according to:

(i) how they were usually expressed in research (i.e. verbal, physical, pictorial, mathematical);

(ii) systematicity (according to Gentner's structure-mapping theory: those with low systematicity have superficial relations which break down if taken beyond surface similarity; while for those with high systematicity a hierarchy of relations holds between source and target domains, from pictorial and physical similarity of the phenomena to similarity of mathematical structures used to represent the phenomena);

(iii) the background knowledge, experience, skills which these analogies often rely on;

(iv) functions (e.g. tools of exploration in private conceptualisation, tools of explanation when conveying novel ideas to colleagues or when communicating basic physics to novices; to play with ideas in informal settings);

(v) context of use;

This is summarised in tabular form. A general definition of the three classes of analogy and a characteristic example drawn from the on-line questionnaire data are provided for clarity.

Expressed As	Verbal / Physical / Pictorial Analogies	Physical and Pictorial Analogies	(Nomo) (Formal) Mathematical Analogies
Systematicity	Low	Medium to High	High
Definition	The analogies are often novel and amusing, relating abstract physics concepts to familiar, everyday things like dazed chickens, cheese sandwiches, Snickers bars, football stadiums, donuts, etc.	The physical picture attached to one situation can be used to visualise another. These idealised pictures are usually used iteratively: further refined and abstracted through rigorous mathematical and experimental testing.	The same mathematics can be used to describe two situations. Phenomena in one situation will have a counterpart in the second, as the mathematics for the two is identical.
Example	"A Tokamak is like a donut, but filled with plasma instead of cream." Phys_189 "Reversal of magnetisation through a magnetic logic NOT-gate likened to a car performing a three-point turn." Phys_191	"Cerenkov light is created when a particle passes through matter at above the local speed of light. The effect is similar to the skock wave created by an airplane flying at above the speed of sound." Phys_198	"I quite often use the analogy of cold atoms to try to tackle problems in other areas. Cold atoms are a very clean and well understood research topic where I have experience in, and its results are widely applicable also to other areas." Phys_35
Often rely on	Popular associations; Creative imagination;	Geometrical intuition (seeing patterns and symmetries in the underlying mathematics) Kinesthetic awareness (of macroscopic capacities); Tacit knowledge (gained through experimentation);	Geometrical intuition (seeing patterns and symmetries in the underlying mathematics)
Functions **(Epistemological Aims)**	Tools of Explanation. To make physics accessible, memorable and entertaining, in order to enlist support. Occasionally used by expert physicists in private conceptualisation to play with ideas.	Tools of Exploration; Heuristics; Provide physical and pictorial insight; Mechanisms underlying phenomena in analogous systems can be compared & contrasted.	Tools of Exploration; Allow direct comparison of physical systems to be made on an abstract mathematical level. Basis for computer simulations;
Contexts of Use	(1) Private Conceptualisation;	(1) Private Conceptualisation;	(1) Private Conceptualisation;
	(2) Expert-Expert Communication in **very informal** settings; Often used to entertain an audience or to make a point in a lively debate;	(2) Expert-Expert Communication in **formal** and **informal** settings; Use in journal publications is dependent on norms of research area and "in-house style" of journal. Some journals object to creative use of language.	(2) Expert-Expert Communication in **formal** and **informal** settings, including journal publications & presentations to conferences of experts;
	(3) Expert-Intermediate Communication in **informal** settings (used to entertain);	(3) Expert-Intermediate Communication in **formal** and **informal** settings;	(3) Expert-Intermediate Communication in **formal** and **informal** settings;
	(4) Expert-Novice communication (to make physics accessible and memorable by drawing on concepts from everyday life);	(4) Expert-Novice communication (in particular to visualise the unseen, e.g. atomic physics, nano-physics, cosmology and astrophysics, etc.);	(4) Almost never used by physicists to communicate with novices as concepts from the source domain would be unfamiliar to novices.

Table 2.2 A summary of the system of classification I used to determine the forms of analogy used in different contexts

2.4 Method 4: Case study of physicist-engineer who was an enthusiast for analogy and had an interesting research training.

The findings of the initial survey of 225 physicists highlighted several key issues concerning the tools, techniques and problem solving strategies used by a sample of physicists. In particular, the role of analogy in gaining physical and/or pictorial insight, and the affect of training, experience and nationality on conceptualisation and communication techniques, in particular on the use of analogy. Thus, in year two, the study moved from the macro to the micro, carrying out a case study of an individual physicist. My aim was to explicate the conceptualisation and communication techniques employed by a particular physicist-engineer, and to explore how the context in which he worked may have influenced his approach.

Dr. John Lawson contacted me in March 2003 after seeing my request for questionnaire respondents in **Physics World** magazine (2003, Vol.16, No. 3, p.20). In his March 2003 letter he explained that he would have found many of the questions in my on-line questionnaire difficult to answer because, firstly, he had been retired for the past fifteen years and thus had little contact with the physics community, and secondly, the concepts e.g. 'mental picture' were not particularly well defined in his view. He enclosed 10 of his scientific papers (dating from 1950 to 1989) with post-it note annotations regarding his use of analogy.

His enthusiasm for using analogy in his scientific work suggested that he would make an interesting case study subject. In addition, Dr. Lawson's letter of March 2003 touched on several other cognitive, social, developmental, and behavioural factors of the kind detailed in Feist and Gorman's (1998) *Structural Equation Model,* which I was interested in exploring further. In the <u>cognitive sphere</u> he said he was a great enthusiast for analogies, since he liked to think "pictorially and <u>not</u> mathematically". In the <u>social/cognitive spheres,</u> he remarked that he had worked with and delivered lectures to physicists of varying research backgrounds and nationalities and had noticed, in the course of his long and varied career, how research background and nationality affected physicists' use of analogy. In the <u>developmental sphere,</u> he had interesting research training: after acquiring a practically orientated, 2-year, 'war-time' degree in mechanical sciences he worked on airborne radar at the Telecommunications Research Establishment Malvern, then on the design of particle accelerators at Harwell and the Rutherford Appleton Laboratory.

During our first interview I also discovered that he was very well renowned in the area of particle physics. In the late 50s he gave his name to the 'Lawson criterion' (which deals with the conditions needed for a fusion reactor to reach ignition), in 1969 he received an ScD Physics from Cambridge University, in 1985 he was awarded the *Thomas Young Medal* by the Physical Society (given for optics), and in 1988 was elected a Fellow of the Royal Society. Thus, Dr. Lawson was a perfect candidate for a case study. Dr. Lawson contacted me when I was receiving responses from my on-line questionnaire. Although it was tempting to begin analysing his work immediately, I adhered to my research design, explaining to him that I would not begin the case-study until after I had analysed the material from the on-line questionnaire. Dr. Lawson was very patient and accommodating in this and many other respects. A timeline of Dr. Lawson's career path is provided in appendix 7 and an extended outline of his career is discussed in section 7.0.

2.4.1 Summary of Case-Study Specific Research Questions (cf. chapter 1)

- To what extent did Dr. Lawson experience difficulties getting a mental picture of the physical processes in his research?
- What reasons were given by Dr. Lawson for having/not having difficulty getting a mental picture of the physical processes in his research?
- How did educational, professional, cultural, historical, etc. aspects impact on Dr. Lawson's approach to problem solving?
- To what extent did Dr. Lawson use **analogy** to acquire and promote insight?
- How does **physical** insight differ from **pictorial** insight in DR. Lawson's view?
- To what extent did Dr. Lawson use analogy to bridge sub-disciplinary boundaries?
- What types of analogies did Dr. Lawson employ in this context? I.e. were they within domain or between mappings, physical, pictorial, mathematical etc.

2.4.2 Semi-structured interview

A 30-minute semi-structured interview took place on at Dr. Lawson's residence on 15-Jan-2004. Dr. Lawson produced a print-out of the on-line questionnaire and verbally responded to many of the questions, often going off on interesting tangents. As Dr. Lawson was effectively interviewing himself, I attempted to make as few interjections as possible, but did make some for the purpose of clarification, and to compare and contrast Dr. Lawson's views with those of other questionnaire respondents. Throughout, I avoided reference to existing theoretical stances on analogy or visualization. The interview was tape-recorded to provide an accurate record of our discussion. Dr. Lawson exhibited no strong signs of discomfort or inhibition on being tape-recorded and seemed comfortable in his familiar surroundings.

2.4.3 Content analysis and textual analysis of a selection of Dr. Lawson's scientific papers

In his letter of March 2003 Dr. Lawson furnished me with 10 of his scientific papers with post-it note annotations regarding his use of analogy. Personal photocopies were made of these papers, Dr. Lawson's original post-it notes were stapled to them, and the original papers were returned to Dr. Lawson. A search of the *Institute of Physics* on-line journal database produced an additional 9 scientific papers authored by Dr. Lawson. At our first meeting Dr. Lawson provided me with a list of 98 of his "publications and more important unpublished reports" dating from 1946 to 1997, and marked off 11 papers worthy of pursuit (one of which was already in my possession). In the following weeks I procured the remaining 10 recommended papers and, in order to balance the purposive sampling (or 'cherry-picking') of particular papers featuring analogy, 6 others that were in stock in the University of Bath library. [46] This brought the total number of papers in my possession to 35. Passages from these papers, (relating to analogy, physical insight, simplification, training, research communities), were transcribed, colour-coded and ordered chronologically. (Dr. Lawson's post-it note annotations were also transcribed and inserted where relevant.) The aim was to provide a systematic over-view of a broad selection of Dr. Lawson's papers. [47]

[46] Mostly from **Nature** and from **Philosophical Magazine**

[47] From this over-view, one could see that explicit analogies were used in approximately 50% of the sampled papers. However, limiting-case analysis and mathematical simplifications did feature throughout Dr. Lawson's papers, and it was often difficult (for a non-specialist) to identify every mathematical analogue. Thus, this must be taken into account when evaluating the prevalence of analogy in this sample of papers.

2.4.4 Content analysis of Dr. Lawson's book

I obtained a copy of Dr. Lawson's 446-page book, "The Physics of Charged Particle Beams" part of the "International Series of Monographs of Physics". A procedure similar to that outlined above was followed when analysing the book. Approximately 5,500 words of relevant excerpts were transcribed and keywords (e.g. analogy, physical insight, simplification, training, research communities) were colour-coded during transcription to facilitate subsequent analysis and collation. This revealed approximately 55 examples of analogy, including mathematical analogues, physical analogues and pictorial analogues. Examples of pictorial analogues were photocopied for future reference.

2.4.5 Collation of results:

Particularly pertinent excerpts (from the interview transcript, scientific papers and monograph which had been colour-coded during transcription) were then arranged thematically, under the research question headings. The aim was to provide a framework within which to better understand how latent factors, akin to those outlined in Feist and Gorman's (1998) SEM, may have impacted on the tools, techniques and problem solving strategies employed by Dr. Lawson.

2.4.6 Use of a Cognitive Styles Framework As An Investigative Tool

Dr. Lawson, a retired physicist-engineer, was not a designer in the artistic sense considered by Williamson (web ref) [48] or the architectural sense considered by Goel (1995), discussed in section 1.11. However, there are some similarities between the cognitive/working styles of design engineers and physicist-engineers. For example, my subjects deal with ill-structured problems, manipulate representations of the world, and use many different symbol systems that vary according to context, objectives, personal preferences etc. By adapting the cognitive style dimensions of Riding & Rayner (1998) and of Williamson (web ref), a cognitive styles framework was constructed. [49] This framework was used as a tool of investigation and guide in analysing my case-study material. For example, it was used to sort data and frame follow-up interview questions. The goal was not to establish Dr. Lawson's cognitive style(s) and hence generalise that all those who employ analogy

[48] Jack Williamson is Adjunct Assistant Professor of Design Studies, The University of Michigan School of Art. His notes on designer styles were gleaned from a power point presentation which can be found on-line at: www.designmichigan.org/design_futures/powerpoint/plainDesTypes.ppt. Last accessed on 11-01-2005

[49] I assume that Williamson regards working style, sources of inspiration, problem scale, and social-historical dimension to be facets of cognitive style, although it is unclear from the list of horizontal pairings he puts forward. In any case, I have not differentiated between these sub-classes. Instead, I have selected relevant characteristics and integrated them into my more general cognitive styles framework.

exhibit similar cognitive styles. One may choose to infer from my findings that scientists who are enthusiasts for analogy share similar cognitive styles. However, my aim is not to establish this connection. As mentioned in section 1.18, the cognitive styles framework was a very useful map or guide with which to navigate and explore the terrain, e.g. I used it to formulate questions which then led on to other things unrelated to cognitive style.

I carried out a content analysis of 30 of Dr. Lawson's scientific papers, the 2nd edition of his book on the physics of charged particle beams, and our personal correspondence and semi-structured interviews which were carried out at his home and by telephone. In order to explore initial hypotheses e.g. that Dr. Lawson tended to 'synthesise' ideas, often through drawing analogies, I used the cognitive style framework to gather evidence in a systematic manner. This was done by constructing a table consisting of three columns, containing respectively:

- **various cognitive styles** (adapted from Riding & Rayner, 1998; Williamson (web-source), and Goel, (1995);
- **my estimation of the degree to which Dr. Lawson exhibited this characteristic** (based on my analysis of his work and our personal correspondence);
- **excerpts from the data to support these estimations**.

A sample of the cognitive style framework is outlined on the following pages, in tables 2.3 and 2.4.

Characteristic	My Estimation	Supporting evidence
Synthesizer	Very much so	"The approach is synthetic; simple examples are considered first, and the complications introduced gradually...." (The Physics of Charged Particle Beams, 1989, 2nd ed, p.1) "an attempt has been made here to bring together and compare all commonly used versions." (TPOCPB, 1989, 2nd ed, p12)
Generalist	Very much so	"In this monograph, the unity of things encountered in different contexts is emphasised and classification is in terms of physical features rather than application.." **(monograph, p.1)** "I used to say that I was a "jack of all trades and master of one". (Dr. Lawson, March 2004 telephone iv)
Innovative	Very much so (Although Dr. Lawson does not appear to regard himself as particularly innovative. It depends on how one defines innovative.)	"as a boy, I was always making things.." **(Dr. Lawson, Jan 2004 interview)** "as a boy I was always doing experiments and building things.." **(Dr. Lawson, March 2004 telephone iv)** "I'm not sure that I had all that many [ideas]. A lot of my ideas were in showing how things wouldn't work as they were being claimed, especially with new things." **(Dr. Lawson, Jan 2004 interview)** "Often if there's a complicated problem that you don't quite know how to tackle, the thing is to invent a simpler problem of the same class, which you think you can tackle." **(Dr. Lawson, March 04 phone iv)** "I have to invent my own way of thinking about particular problems. Just seeing how certain problems seem to be related in one way or another." **(Dr. Lawson, March 2004 phone iv)** "Not particularly [innovative]. I don't think I've invented any new thing, but I'm a good critic really." **(Dr. Lawson, March 2004 phone interview)**
Hands-On	Very much so	"I regard myself as a sort of engineer-physicist, I think. I mean as a boy, I was always making things,..." **(Dr. Lawson, January 2004 interview)** "I had a Faraday-type approach where most of my colleagues were Maxwell like." **(Dr. Lawson, Feb 2004 letter)** "I did a degree in engineering...You have your feet on the ground a bit more if you're an engineer." **(Dr. Lawson, March 2004 phone i.v.)**

Table 2.3: A technique I employed when developing a cognitive styles framework

Characteristic	My Estimation	Supporting evidence
Preference for visual & aural structure	Very much so	"I like something that has a form and a structure to it." **(Mar 2004 iv)** "I enjoy things that are **structured**." **(March 2004 iv)**
Seeks physical & pictorial insight	Very much so	"I think pictorially and <u>**not**</u> mathematically." **(March 2003 letter)**
Intuitive	Very much so	"Often, I think, it's better to go back to the physics, and look at the essentials, and in fact, solve a problem that is easier than the one that we want to solve but it's the same nature." **(Jan 2004 interview)** "I'm not one for emphasising rigour in the early development stages of a subject. In fact, I think the more we keep away from rigour, the better it is. And this joke about a calculation…'assume a spherical elephant'…well, I would approve of that…Very often you can see, rather simply, that this is not a profitable way of going…" **(Jan 2004 iv)**
Wholist	Very much so	"…what I have done is merely to collect together and display as a single exhibit a number of well tried old approaches. I believe however that it is worth while having a clear idea of what the really fundamental constraints are, so that instead of banging our heads against the wall of our prison we can stand back to see whether it has a door." **(J.D. Lawson, 1971, "Diversity and unity in sources and beams," p1)**
Possesses Interactional, Contributory & Communicatory Expertise [50]	Very much so	"I spent a lot of time [doing lectures at conferences and attending workshops]. And I was quite - - well, my style was, I think, quite popular, in that I was, you know, invited all over the place. I went to various European countries - Poland and Romania, Hungary - and I had a special invitation to Russia and to China …and I spent some time in Japan. So these were all just because I seem to have got a reputation for putting things in a way that people liked -- it must have been I think." **(Jan 2004 Interview)** "I used to work largely on my own…and then just appearing and interacting at workshops and conferences which we often had- - and I always used to - - I seemed to go down quite well, and often got invited to give the opening talk or concluding talk to sum it up." **(March 2004 phone interview)**
Independent	Very	"I was rather a timid person…a bit of a 'loner' in my research…" **(Jan 2004 interview)** "I was better working on my own rather than as a team member, so I was just allowed to do what I wanted to." **(Jan 2005 phone interview)**
Collaborative	Quite	In 1952 J.D. Lawson was leading the team developing the X-band Klystron.

Table 2.4: A technique I employed when developing a cognitive styles framework

[50] See Collins & Evans, 2002, p.254

2.4.7 Telephone interviews with Dr. Lawson to test hypotheses generated through using cognitive styles framework.

Using the cognitive styles framework, I formed some initial hypotheses about the tools, techniques and problem solving strategies used by Dr. Lawson in different contexts. I then formulated a list of pertinent questions and conducted a 30-minute 'semi-structured' telephone interview with Dr. Lawson[51] in order to explore my hypotheses concerning the techniques he used to conceptualise and communicate physics. The interview questions explored:

(i) the tools, techniques and problem solving strategies that he used in his work;

(ii) specifically the role of analogy as a means of providing 'insight';

(iii) whether there had been a historical shift in the meaning of the term 'analogy';

(iv) the extent to which Dr. Lawson's early training influenced his research style;

(v) degree to which audience composition influenced Dr. Lawson;

Dr. Lawson's responses were evaluated within my cognitive styles framework and a better understanding of how the contexts in which he employed certain tools, techniques and problem solving strategies was acquired. This process was repeated several times in order to hone my understanding of e.g. how the atmosphere in which he worked impacted on the ways in which he conceptualised and communicated physics. For example:

- On 04-Oct-2004 Dr. Lawson returned a completed questionnaire sent by me on 15-08-2004. It details what he means by the term 'insight'.
- On 14-Nov-2004 I sent J..D. Lawson a questionnaire concerning the contexts in which he found certain conceptualisation and communication tools useful and the atmosphere in which he worked. I ask that he give me his responses by telephone at some point.
- On 13-Jan-2005 we carried out a semi-structured interview by telephone exploring the issues raised in the questionnaire of 14-Nov-2004.
- On 07-Jan-2006 I sent Dr. Lawson 3 draft chapters based on his work. After a cursory glance of the content of these chapters he agreed to waive his right to anonymity.
- On 01-Feb-2006 Dr. Lawson returned the draft chapters (with annotations) and remarked: "as far as I can tell you have given a fair and accurate account of our interviews and painting a flattering picture of me from a study of my published papers and other people's comments. Best wishes and good luck for the future."

[51] On 22-March-2004

In chapters 7 & 8 I build on the information gathered using the cognitive styles framework and discuss Dr. Lawson's role as a synthesiser and translator of ideas between experts in his fields of interest. I show that the atmosphere in which he worked contributed greatly to his use of analogies to conceptualise and communicate physics. For example, during a formative time in his career he worked at Malvern in close-knit teams where informal modes of communication was encouraged. As we will see in section 6.6, analogy is used to a greater extent when the tone of the discussion is informal. Then later in his career he was given the freedom to pursue his own research interests, gaining experience in five separate sub-fields of physics and engineering. This wider field of view contributed to him noticing and using analogies to provide and promote insights to his colleagues.

Thus, a major strength of the project was that the findings from one strand of investigation were used to inform and shape subsequent investigations. First, in our first interview, I drew on the findings from the questionnaire when I asked Dr. Lawson if the complexity of the analogy would increase directly proportionally to the expertise of the target audience. Secondly, Dr. Lawson said he liked to think pictorially and not mathematically. Therefore, in my follow-up e-mail exchanges with 13 physicists and in my interview with Prof. Berry I asked about how best to communicate to physicists having different modes of thought. For example, were analogy and computer simulations useful tools in this context? As you can see in chapters 4 and 5, these focused e-mail and interview exchanges provided a deeper understanding of the key areas of interest.

2.5 Method 5: Follow-up e-mails with a select sample of questionnaire respondents to enquire further into the techniques they use to conceptualise and communicate physics.

After analysing the on-line questionnaire data and beginning my case study of Dr. Lawson's work I had identified several research questions requiring further investigation. For example, whether the use of analogy was more accepted and widespread in certain branches of physics than others., whether analogy constituted a substantial method of scientific innovation etc. 30 physicists were singled out for the follow-up e-mail correspondence. The following criteria were taken into account when selecting them:

(i) Age;
(ii) Gender;
(iii) Research background;
(iv) Do/(do not) have difficulty getting a mental picture of physical processes;
(v) Do/(do not) use analogy to conceptualise and communicate physics;
(vi) Do/(do not) use computer simulations as visualization tools;
(vii) Depth and clarity of original questionnaire replies;
(viii) Have agreed to be contacted in future;

The characteristics of these 30 physicists is summarised in tables 2.5 and 2.6 on the next page.

Age range (in years)	19-29	30-39	40-49	50-59	60-67
Number within this age range	8	8	4	8	2
Number that were male	27				
Number that were female	3				
Research Background	An attempt was made to have a combination of classical physics and quantum physics, theoretical physics and experimental physics.				

Table 2.5: Characteristics of the 30 physicists who were selected for follow-up e-mail enquiries.

The questionnaire's 7-point scale ran from "1/never" to "7all the time".		Never/1	2	3	4	5	6	7/All the time
Difficulties getting mental picture of physical processes.	For example 3 physicists said they never find it difficult to get a mental picture of the physical processes in their research	3	11	5	2	5	2	1
Use Analogy in their research	14 physicists said they use analogy all the time in their research	1	0	3	1	4	7	14
Use computer simulations in their research	4 physicists selected "3" on the 7 point scale regarding the use of computer simulations in research	6	2	4	6	5	1	6

Table 2.6: A selection of questionnaire responses regarding visualisation, analogy and computer simulations from 30 physicists who were selected for follow-up e-mail enquiries.

Respondents were asked questions like the following:

- "**Q.** In your research, do you use an analogy as scaffolding, often discarding and forgetting it after it has served as a bridge when building new explanations and models? Or do the analogies you use in the early stages of your research usually make it into your personal notebook (or equivalent) and then into your research papers, perhaps in an adapted form?"
- "**Q.** You said that only occasionally do you find it difficult to get a mental picture of the physical processes involved in your research because you find 'geometry and patterns...very easy to visualise' as a result of studying, ' too much organic steric chemistry as an undergrad.' What visualization tools did you use when you were studying 'too much organic steric chemistry'? For example, did you use physical models, free-hand sketches, computer visualizations, etc.? I ask because I would like to explore whether formal training in specific visualization techniques might benefit physicists who experience visualization difficulties"
- "**Q.** In your opinion, could all of physics benefit from theoreticians presenting their work in a more visualisable form? [52]Or is that simply not practical because many theorists are skilled at 'constructing mental pictures of mathematical structures' and prefer this approach?"
- "**Q.** Are computer visualisations the best alternative visual aid? Or could physicists learn specific visualization skills (what some respondents have called "tricks") that would assist them in their attempts to 'visualize equations into their physical meaning'? Because as you [/ one respondent] said, when 'trying to imagine NEW laws - computer simulations won't work because one needs the laws to put into the computer to simulate."

13 of these 30 physicists responded to my follow-up queries. As one can see in tables 2.7 and 2.8 on the following pages, the majority of these respondents had stated in the on-line questionnaire that they had a tendency to employ analogy frequently. However, as my aim was to provide a detailed account of the forms of analogy used in different contexts, not to make generalizations about how widespread the use of analogy is, the fact that the sample of follow-up responses is skewed towards enthusiasts for analogy is not problematic. These 13 respondents had provided some of the most revealing responses to the initial on-line questionnaire, so their continued input was particularly valuable.

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[52] With hindsight, 'visual sense' would have been better than 'visualisable' because, as mentioned previously, there is a subtle philosophical distinction between 'visualization' and 'visualizability'.

Respondent ID	Age	Gender	Job title	Research interests (re-coded for the purpose of this table)	Difficulty getting a mental picture of physical processes	Why?	Use Analogy in Research	Generate original analogies in research	Use computer simulations as visualization tools
Phys_2	27	Male	Phd Optoelecrtoincs	Opto-electronics	3 /7	No tangible evidence for whats going on.	7 /7	5 /7	3 /7
Phys_19	60	Male	Professor of Theoretical Physics	Condensed matter	1 /7	Excellent visuo-spatial iq	7 /7	5 /7	7 /7
Phys_27	25	Male	PhD student	Carbon nano-tubes	3 /7	Geometry and patterns I find very easy to visualise, too much organic steric chemistry as an undergrad.	6 /7	5 /7	3 /7
Phys_54	40	Male	Lecturer in Theoretical Physics	Quantum physics	5 /7	I'm interested in quantum gravity which does not exist as a theory yet and may require a reformulation of the nature of space and time at some level. If one sticks to known models then it is possible to visualise things; otherwise it gets difficult.	7 /7	5 /7	3 /7
Phys_57	37	Male	Senior Lecturer in Coastal Engineering	Coastal engineering	2 /7	My understanding is usually pictorial / by analogy. Possibly because my mathematical thinking is weaker.	7 /7	4 /7	4 /7
Phys_91	47	Female	Professor of Astrophysics	Astrophysics	2 /7	I have a strong spatial imagination - have never had difficulty with maps, direction-finding, pattern recognition, can draw quite well. I sometimes get stumped by extreme instances of 3-D imagining.	5 /7	2 /7	5 /7
Phys_128	37	Male	Professor in Theoretical Physics	Artificial black holes, emergent space-time geometries quantum optics, etc.	6 /7	If I have got the mental picture the research is mostly done. So getting the picture is as difficult as doing research. Here the difficulty depends on the choice of topic.	7 /7	6 /7	1 /7

Table 2.7: Initial questionnaire responses of the physicists who responded to my follow-up e-mail queries.

Respondent ID	Age	Gender	Job title	Research interests (re-coded for the purpose of this table)	Difficulty getting a mental picture of physical processes?	Why?	Use Analogy in Research	Generate original analogies in research	Use computer simulations as visualization tools
Phys_150	56	Male	Research Assistant	Detectors for High Energy Physics and Astronomy.	1 /7	Not a problem: neat visualisation is half the fun!	7 /7	6 /7	6 /7
Phys_160	52	Male	Reader in Theoretical Physics	Thermal quantum field theory; applications to cosmology. Phase transitions.	5 /7	Because the basic entities with which quantum theory (and to a lesser extent relativity) deal are not directly observable, and behave in ways for which everyday experience provides no reliable analogy.	3 /7	2 /7	4 /7
Phys_185	45	Female	Research Fellow	Quantum computing	2 /7	The physical world behaves differently at very small scales, you can't directly see/experience what goes on so you have to infer from measurements that translate the information into larger scale changes you can directly see.	3 /7	2 /7	5 /7
Phys_193	31	Male	PhD student	High temp. superconductors	2 /7	I've not fully understood the problem	7 /7	7 /7	7 /7
Phys_200	61	Male	Semi-retired, self employed	cement industry consultant, process engineering, etc.	2 /7	My brain is mainly visual and not strongly mathematical(numerical). (Mild)Dyslexia could have an impact on this although the word had not been coined when I was at school/university.	6 /7	3 /7	1 /7
Phys_202	50	Male	Senior Lecturer in Geophysics	Geophysics	2 /7	I seem to have an ability to visualise the objects and the fields in both 2 and 3 dimensions. I first realised this, consciously, when I had just started my PhD. I could "see" the object that was generating an anomalous response, just from the shape of the response.	6 /7	3 /7	3 /7

Table 2.8: Initial questionnaire responses of the physicists who responded to my follow-up e-mail queries.

2.5.1 Several rounds of particularly detailed responses from Phys_54 on issues concerning visualization techniques, including thought experiments.

This questionnaire respondent (based in Australia) provided 4 rounds of extremely detailed e-mail replies to my queries concerning visualization techniques. He provided some extremely interesting comments on his use of thought experiments to conceptualise and communicate his research. (His responses appear in sections 3.5, 3.6 and 3.7). In the on-line questionnaire I chose not to include questions concerning the use of thought experiments as visualization tools as my 'test-questionnaire' (distributed to physicists based at the University of Bath) suggested that the term 'thought experiment' was too profound and philosophical a description of what these physicists said they did in their work, and it also made the questionnaire too long. However I did ask respondents to select from a 7-poiint scale in order to indicate to what extent they visualised experiments which were (i) then physically performed, (ii) too expensive or technically difficult to physically perform, (iii) physically performable, but doing so would offer no further insight, (iv) impossible to physically perform. Thus, I have included the data from this question in section 3.7 alongside the follow-up e-mail comments of Phys_54 concerning his use of thought experiments.

2.5.2 Follow-up e-mail exchanges with Prof. Paul Coleman to enquire into the origins of the Dazed Chicken Analogy he employed in his inaugural lecture.

Prof. Paul Coleman responded to the on-line questionnaire. In fact, he referred to the questionnaire when he introduced his *Dazed Chicken Analogy* sketch during his highly entertaining inaugural lecture.[53] I had several e-mail exchanges with Prof. Coleman in order to ascertain the creative origins or the sketch, his aims when employing the sketch, the feedback he has received from his colleagues and students to his use of the sketch etc. The data from these e-mail exchanges appears in sections 6.6.3 and 6.7.1 on the use of analogy in science communication.

[53] ***"Probing Matter with Anti-Matter: A Career in Self-Annihilation,"*** delivered the University of Bath, on 01-05-2003

2.6 Method 6: In-depth interview with Prof. Berry to focus on the techniques he employs to conceptualise & communicate quantum physics

A semi-structured interview was carried out with Prof. Sir Michael Berry at his office at Bristol University. He had not responded to the on-line questionnaire, but is highly regarded as a theoretical physicist and science communicator and his scientific pictures have won several awards. In the semi-structured interview I focused on the techniques he uses to acquire and promote insight in quantum mechanics. As the interviewee had the freedom to digress, we explored some very interesting tangents. For example, Prof. Berry drew my attention to Physical Review Letters censorship of creative language. This is a particularly interesting point, because it ties in with the fact that playful analogies and other creative use of language are unacceptable in certain media. This discovery highlights one of the great strengths of semi-structured interviews: their ability to uncover information which is highly relevant but which would not have come to light through the use of more structured forms of data gathering. The data from this semi-structured interview appears in sections 4.8 – 4.12, on the use of computer simulations when conceptualising and communicating physics with experts, intermediates and novices.

2.7 Expertise: Establishing oneself as a worthy (associate) member of the physics community.

In the early stages of my case-study investigation, Dr. Lawson (my case-study respondent) expressed some concerns about my study. For example, he asked: What were the aims and objectives of my study? How could I isolate variables? How could I generalise from this one case study? Exactly how much physics expertise did I possess? Did I have sufficient understanding of the subtleties of the physics contained in his papers and book to properly analyse and comment upon them? I explained that my intention was not to generalise from this one case study. Rather, I wished to explicate the conceptualisation and communication techniques used by one particular physicist and explore how the contexts in which he worked may have influenced his approach. I also explained that though I would like to become an expert in the research areas of all of my respondents, I did not have the time. My clarifications concerning my aims, objectives, methodological approach and expertise assuaged Dr. Lawson's initial concerns. Sociologists of Scientific Knowledge are often confronted with these types of questions as they attempt to gain a foothold in a domain in which they have little or no expertise. Harry Collins has highlighted this issue on many occasions in his studies of physicists working on gravitational waves.

In a recent paper, Collins and Evans define three types of expertise that a sociologist of scientific knowledge may possess:

1) "No expertise: That is the degree of expertise with which the fieldworker sets out. It is insufficient to conduct a sociological analysis or do quasi-participatory fieldwork.

2) Interactional Expertise: This means enough expertise to interact interestingly with participants and carry out a sociological analysis.

3) Contributory Expertise: This means enough expertise to contribute to the science of the field being analysed." (Collins & Evans, 2002, p.254)

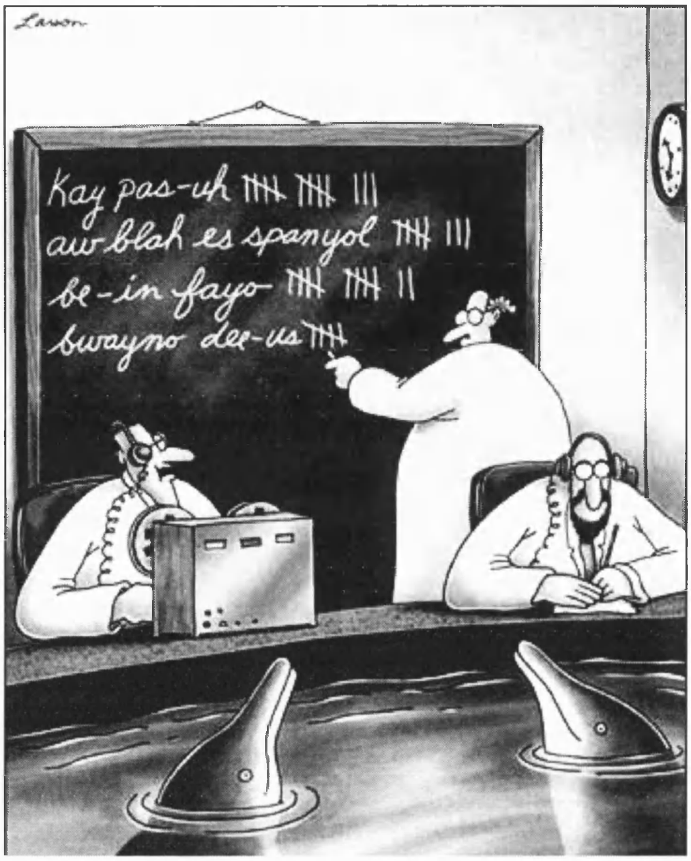

Figure 2.1: (Copyright Gary Larson)

Caption reads: ***"Matthews…we're getting another one of those strange 'aw blah es span yol' sounds."***

Within this classification scheme, I could be said to possess "interactional expertise" but not "contributory expertise". However, Gooding (via personal communication, July 2004) points out that the Collins-Evans classification is research-focused and does not consider communication aspects, and suggests splitting 3 into: "(3a) research contributory expertise; (3b) – communicatory expertise." Adding, "clearly these two overlap, but I'd say you have competence in 3b. Any science writer must have." [54]

[54] This Gary Larson cartoon seemed like a nice way of highlighting this notion of expertise. In the early days of my PhD research I was concerned that I may not have quite enough expertise in physics, psychology, sociology, philosophy, etc. to carry out investigations into the visualization techniques used in cognition and communication in physics. I would like to thank Prof. David Gooding, Prof. Helen Haste, Dr. Chris Philippidis and many colleagues from the departments of psychology, education, physics, and computer science for giving me faith in my own abilities.

Someone who undoubtedly possesses what Collins calls "interactional expertise" is the anthropologist, Sharon Traweek. She has spent over three decades observing the international community of high-energy physicists. [55] According to Traweek:

> "Protection of oral communication encourages the development of a closed community. In physics it is consistent with the group's image of itself as a meritocracy: only an informed, worthy member of the community will know what is to be said and what is to be written." (Traweek, 1988, p.120)

Thus, Dr. Lawson's reticence was entirely understandable, particularly in the light of Traweek's findings.

2.8 Ethics

In accordance with ethical guidelines, interviewees were provided with a brief over-view of my research project and a consent form at our first meeting. The consent form asked interviewees if they would waive anonymity on condition that they would have the opportunity to proof-read and amend thesis chapters to which they contributed. Bailer-Jones (2002) used a similar approach in her analysis of nine interviews of UK scientists on the topic of scientific models.[56] All questionnaire respondents remain anonymous but, on the suggestion of one respondent, their valuable input was acknowledged in an alphabetical listing in the appendix of the thesis. I aim to provide full access to my thesis on-line and publish a summary of my findings in popular science magazines such as Physics World in order to provide feedback to the physics community. Thus, this project is, to a certain extent, 'action research' because it is my hope is that these findings will lead to a different approach to the use of these model-based reasoning techniques in physics education and communication. For example, I hope that educators will work with practicing physicists to develop better analogies that can be used in a more structured way which is less likely to mislead students.

[55] Traweek conducted field research for two years at SLAC [the Stanford Linear Accelerator Centre], three years at KEK [the Japanese National Physics Laboratory] at Tsukuba, Japan, six months at Fermi National Accelerator Laboratory in Illinois, and shorter visits to CERN [European Centre for Nuclear Research] in Switzerland, DESY [electron synchrotron facility] in Germany, and the Saclay laboratory in France),

[56] Bailer-Jones' rationale was that: "the interviewees are, as scientists, trained and able to undertake such rationalizations [of what scientific models are and how they use them] and they are experienced speakers, so there is little risk of putting them into an uncomfortable, difficult situation by questioning them about models. This is why, for instance, I see no particular need to make anonymous the presentation of my results, a mandatory procedure in a sociological research context. " (Bailer-Jones, 2002, p. 277)

Chapter 3:

In Search Of Enlightenment: Visualization Techniques Employed By A Sample Of Physicists.

“Mighty is the charm
Of these abstractions to a mind beset
With images, and haunted by herself,
And specially delightful unto me
Was that clear synthesis built up aloft
So gracefully; even then when it appeared
Not more than a mere plaything, or a toy
To sense embodied: not the thing it is
In verity, an independent world,
Created out of pure intelligence.”

William Wordsworth,
The Prelude, Book Six, Cambridge And The Alps.

3.0 Overview:

This strand of the research explores visualization in physics. The data is derived from 225 responses to an on-line questionnaire on visualization and analogy in contemporary physics,[57] follow-up correspondence with a select sample of 13 questionnaire respondents [58] and a semi-structured interview with a distinguished theoretical physicist.[59] First, I present data on the degree to which these physicists reported finding it difficult to get a mental picture of the physical processes involved in their research. Second, I detail the reasons they gave for this. Third, I give an overview of the many visualization techniques these practicing physicists reported using when building & adapting their theories, models and experiments. The on-line questionnaire had additional detailed questions on the role of **analogy** and **computer simulations** as specific visualization tools. This will be presented and discussed in chapters 4, 5 & 6. This chapter sets the scene for these subsequent discussions. Lastly, I enquire into whether the kinaesthetic skills of sketching, and physical & mental modelling are vitally important in helping a sample of physicists to visualise physical processes in their research, and whether they have developed these skills on their own or have learned them through formal education. It would seem from my initial enquiries that while such skills are vital components in a physicists' toolkit, rarely are they enshrined in the curriculum.

[57] Received between February and May 2003
[58] Received between 31-05-2005 and 20-01-2006)
[59] Professor Sir Michael Berry, conducted at his office at the University of Bristol, on 05-07-2005

3.1 Background information on questionnaire respondents.

As outlined in chapter 2, the first section of the on-line questionnaire asked respondents to state their 3rd level qualifications, the branches of physics with which they would associate themselves (they were given a list of 12 to choose from), their age, gender, current occupation or course of study, research interests, etc. As you can see in figs. 3.1 and 3.2 the age ranges and occupations of respondents provided an excellent cross section of the physics community. The IoP groups with which respondents associated themselves were also well distributed, but had a definite clustering around Astrophysics. Analysis of this background information revealed an apparent relationship between age and views on computer simulations (see section 4.6.4). However, the aim was not to identify statistically significant correlations between e.g. gender and visualization difficulties. In general, the information was used in a qualitative manner when interpreting an individual's response to a given question. So for example, the responses of a 25-year old PhD student, studying quantum computing (identified as **Phys_221**) were interpreted slightly differently from those of a 65-year old Professor of condensed matter physics (identified as **Phys_222**). The accompanying CD contains an excel file containing the entire questionnaire dataset, including respondents research backgrounds and replies to questions on visualisation, analogy, computer simulation and physics communication. The "*edit - find*" facility in excel is useful for locating comments pertaining to specific things, e.g. sketches, reality, models, abstract, etc.

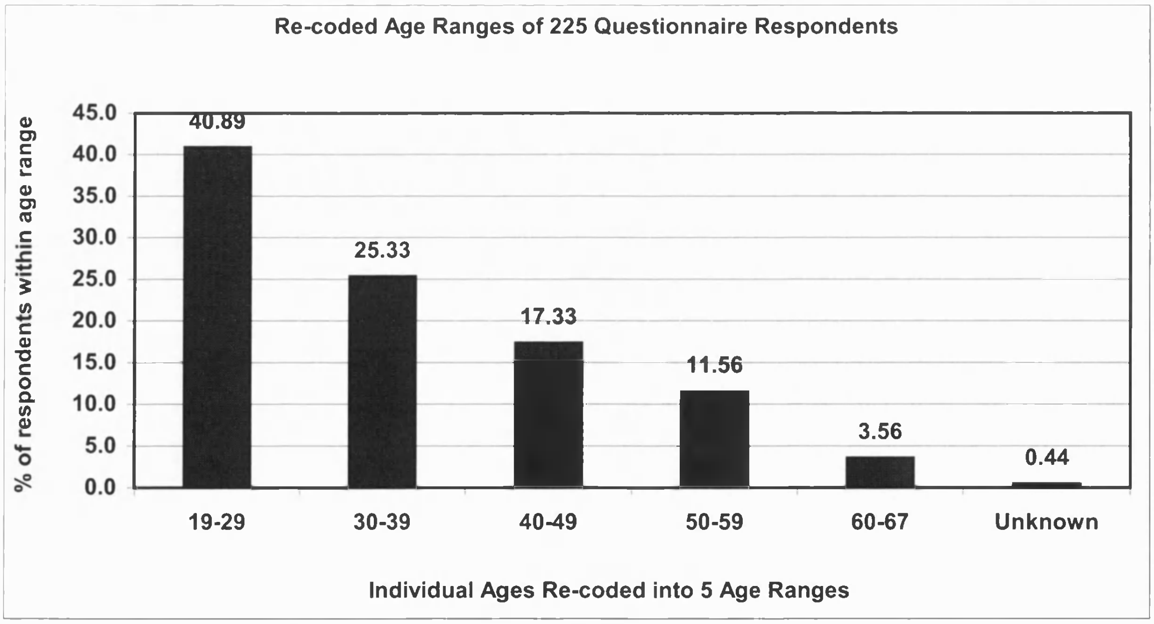

Figure 3.1: Chart indicating the % breakdown of age ranges of 222 respondents.

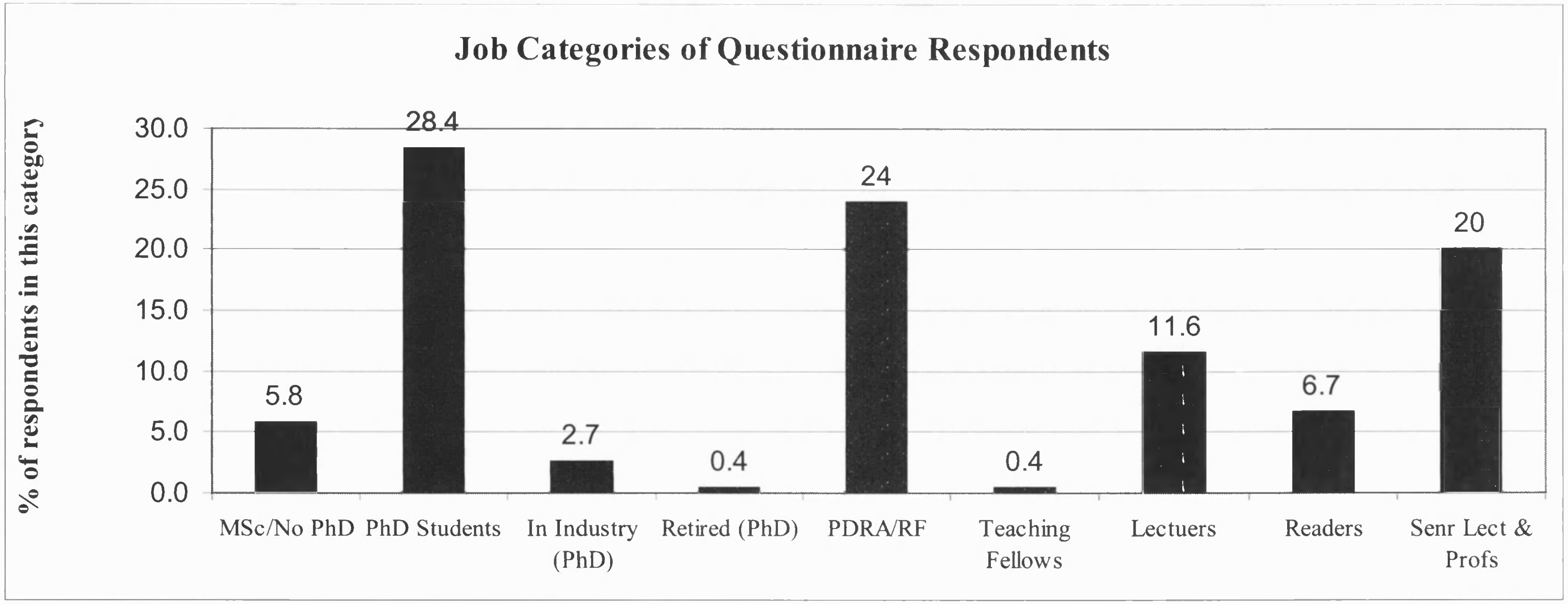

Figure 3.2: Chart indicating the job categories of 225 respondents. The data provided by respondents has been re-coded as follows:

Category 1: Hold an MSc but no PhD
Category 2: Pursuing their PhD's
Category 3: Hold a PhD. Now work in industry.
Category 4: Hold a PhD. Now retired.
Category 5: Post-Doctoral Research Associates or Research Fellows
Category 6: Teaching Fellows
Category 7: Lectures
Category 8: Readers
Category9: Senior Lectures and Professors

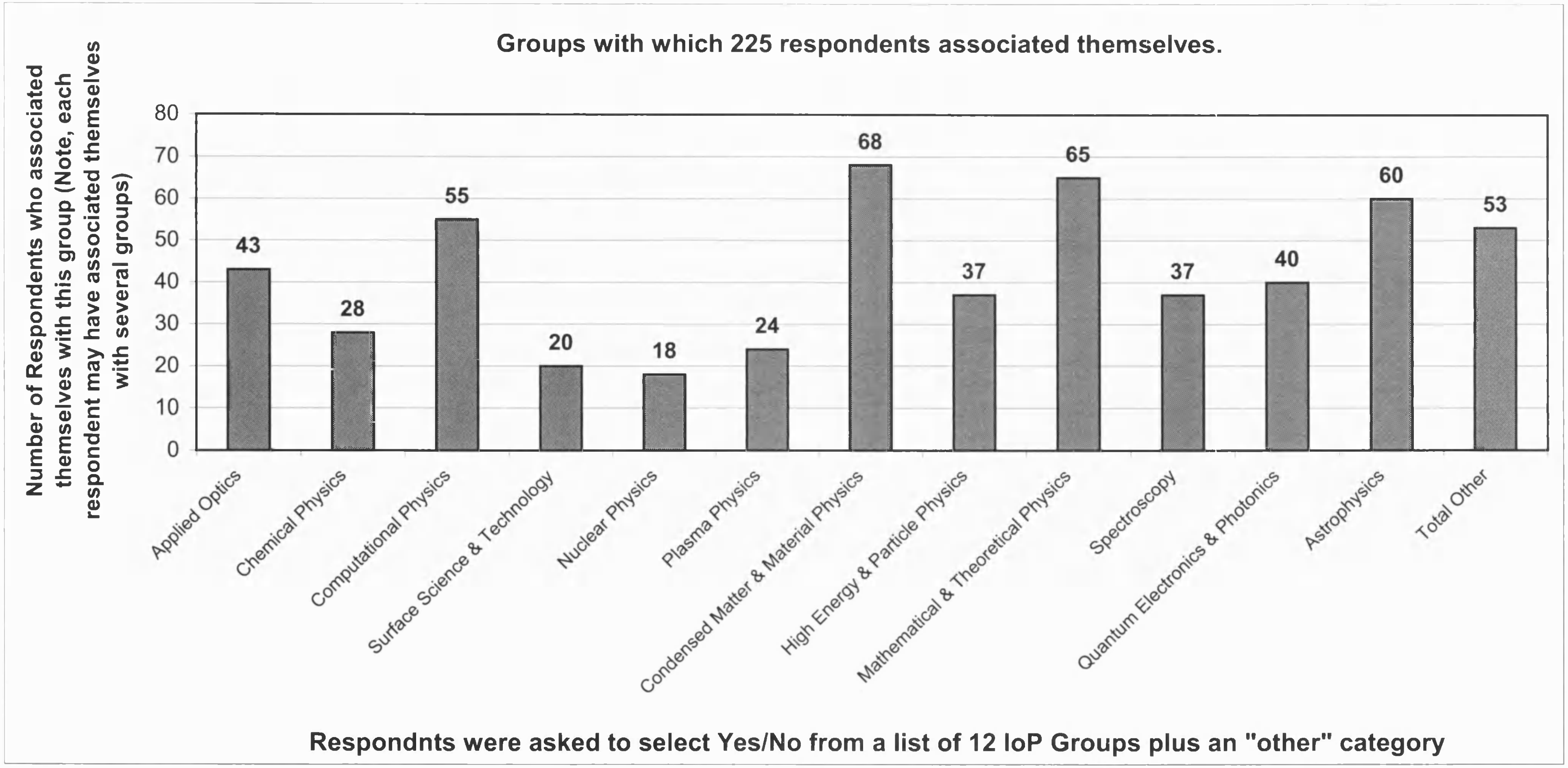

Figure 3.3 Chart indicating the groups with which respondents associated themselves.

Interestingly, of the 60 respondents who associated themselves with "Astrophysics", 35% associated themselves with just this one group. In comparison, of the 43 respondents who associated themselves with "Applied Optics" only 9.3% associated themselves with just this one group. This may be an indication of the extent to which Astrophysics is a more distinct community.[60] (See appendix 3 for a tabulated summary of the number of groups with which respondents associated themselves).

3.2 Do physicists ever find it difficult to get a mental picture of the physical processes involved in their research?

Question two of the online questionnaire posed the following question: *"Do you ever find it difficult to get a mental picture of the various kinds of physical processes involved in your research?"* Respondents chose from a 7-point scale ranging from "1/never" to "7/all the time". As can be seen in table 3.1 and figure 3.4, there was a skew towards the "seldom find it difficult" end of the scale, with 66.7% of respondents selecting from the (1-3) range; 15.6% selecting the midpoint (4); and 17.8% selecting from the (5-7) range i.e. the "often find it difficult" end of the scale. Only 3.6% of respondents said that they find it difficult to get a mental picture of the physical processes involved in their research "7/all the time". This compares to 9.8% of respondents who said they "never/1" find it difficult.

7-point semantic differential scale	**Frequency**	**Valid Percent**	**Cumulative Percent**		
Never/1	22	9.8	9.8		
2	73	32.4	42.2		
3	54	24.0	66.2	**Statistics**	
4	35	15.6	81.8	Mean	3.09
5	29	12.9	94.7	**Median**	3.00
6	4	1.8	96.4	**Mode**	2
7/all the time	8	3.6	100.0	**Std. Dev.**	1.4
Total	**225**	**100.0**	**100.0**		

Table 3.1: Statistics regarding the extent to which questionnaire respondents find it difficult to get a mental picture of the physical processes involved in their research.

[60] An attempt was made to pursue this issue in follow-up e-mail exchanges with some of the physicists who associated themselves with Astrophysics, but no replies were received. The e-mail addresses may have become obsolete in the intervening 2 years or the question may have been too daunting.

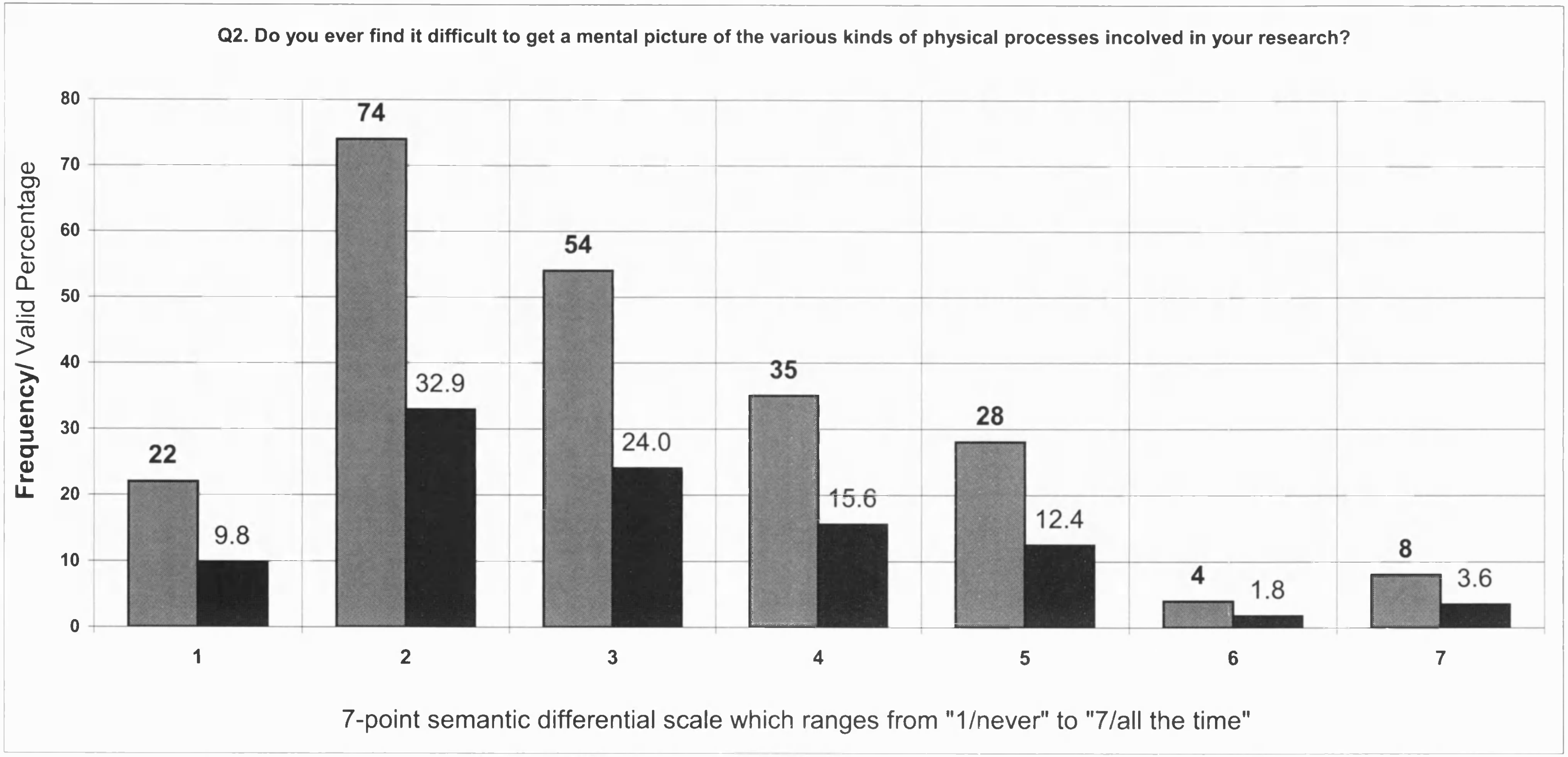

Figure3.4: Chart showing quantitative data on the degree to which respondents say they have difficulty getting a mental picture of the physical processes involved in their research.

Question **2** of the on-line questionnaire was followed by question **2b** which asked: *"Why do you think this is?* As discussed in chapter 2, the qualitative responses were re-coded to give an indication of the frequency of occurrence of certain common factors. Each respondent's research background and research interests were taken into account when interpreting the qualitative responses. Thus, for example, an attempt was made to distinguish respondents who regularly dealt with quantum physics from those who tended to employ classical or semi-classical physics. A summary of the re-coded qualitative data is presented below. The numbers are approximate and do not add up to 225 as comments sometimes overlapped between categories.

3.2.1 Reasons given by respondents for having difficulties

Approximately 47 respondents said their difficulties were due to the ***abstract*** or ***complex*** or ***theoretical*** nature of their subject. 28 said their difficulties were due to the numbers of ***dimensions*** or the complex ***symmetries*** involved. 23 said they had difficulties because they worked with ***quantum*** concepts for which visualization was extremely difficult. For example, **Phys_160** (a 52 year old Reader in Theoretical Physics) said his difficulties arose "Because the basic entities with which quantum theory (and to a lesser extent relativity) deal are not directly observable, and behave in ways for which everyday experience provides no reliable analogy." 22 respondents said that they had difficulties because they had to deal with areas outside their ***expertise*** (e.g. because their work was multi-disciplinary or because they had recently moved to a new area of research, e.g. biophysics); 18 said the had difficulties because their research was ***difficult to relate to everyday concepts*** (these were distinct from those that mentioned quantum physics specifically); 14 said their difficulties arose from the number of ***interacting processes*** and their ***counter-intuitiveness***; 11 didn't know what accounted for their difficulties; and 4 simply said physics is supposed to be difficult.

3.2.2 Reasons given by respondents for <u>not having</u> difficulties

The comments of 33 respondents suggested that they did not have difficulties because they have good ***innate abilities*** (mathematical, visuo-spatial, etc). For example, **Phys_121** (a 59 year old Prof. of Physics) indicated that he very rarely has difficulty, adding: "Both my parents were artists - I'm a very 'visual' person. I've had plenty of practice thinking in pictures and in three dimensions." 15 respondents said their subject was ***easy to visualize***. For example **Phys_77** (a 33 year old PDRA) indicated that he very rarely has difficulty, adding: "Optics is quite understandable in terms of getting a mental picture." 7 respondents said it comes with *practise and specific training*. For example, **Phys_ 119** (a 48 year old university lecturer) indicated that she "never" has difficulty on account of: "Long practice, starting as a small child (age 8?). Most difficult was electricity -- solved by using mechanical analogies."

Many respondents who seldom found it difficult to get a mental picture of the various kinds of physical processes involved in their research, would not or could not explain why this was the case. This is not particularly surprising: if they had no visualization difficulties they would not have spent much time thinking about issues surrounding visualization. 6% of the sample (i.e. 13 respondents), offered "don't know/blank" replies, of which: 5 respondents selected **1**: [on the 7-point scale], 4 respondents selected **2**; and 3 respondents selected **3.** This resulted in a mean value of ***1.8***.

Having analysed all the qualitative and quantitative data from the on-line questionnaire, I have identified four broad factors accounting for the varying degrees of visualization difficulties experienced by respondents. These are subject matter, innate abilities, training, and experience. This is summarised in table 3.2 below.

FACTORS	Visualization Difficulties lessened by the following factors:	Visualization Difficulties compounded by the following factors:
Subject matter	- easy to visualise; - on a human scale; - 3 dimensions at most; - easy to identify and isolate interactions; - deal with a well-developed area.	- abstract nature, complex symmetry; - on microscopic/gigantic scales; - between 3 and 10 dimensions; - lots of interacting processes; - new unexplored area.
Innate abilities	- Have good mathematical, visio-spatial, technical, verbal, social abilities	- Have poor (or under-developed) mathematical, visio-spatial, technical, verbal, social abilities
Training	- Previously learned methods can be applied to problem (e.g. Feynman diagrams);	- Previous learned methods cannot be applied to problem.
Experience	- Is an expert at particular area of focus, - Easy to relate to everyday experience, and can often proceed intuitively.	- Is a novice at particular area of focus, - Difficult to relate to everyday experience, and often counterintuitive.

Table 3.2: Summary of factors which account for respondents visualization difficulties

3.3 Techniques Used To Overcome Visualization Difficulties.

In his book ***"Doing Physics - How Physicists Take Hold Of The World",*** Martin Kreiger tells us that **A Physicist's Toolkit** consists of three main types of tools: mathematical, diagrammatic, and rhetorical. These are subdivided by Krieger as follows:

1. **"Mathematical Tools**
   a. **counting and approximation:** statistics and combinatorics.
   b. **pattern:** geometry, symmetry, conservation laws.
   c. **linearity:** calculus and optimisation procedures
2. **Diagrammatic Tools**
   a. **geometric and spatial**: vectors and graphs.
   b. **patterned algebraic expressions**.
3. **Rhetorical Tools**
   a. **media:** spacetime vacuum, crystal, hydrogen atom, gas.
   b. **objects:** particles, oscillators, fields, waves.
   c. **interactions:** collisions, Lagrangians, response functions.
   d. **strategies of address:** find a good vacuum, or ground state, or equilibrium; group objects into families; find nicely separable parts; divide the labour among specialists.
   e. **Commonplaces or qualitative methods**, such as using a classical picture supplemented by quantum rules." (Krieger, 1992, p.116)

Krieger's categorisation is misleading if interpreted rigidly. Mathematical tools and diagrammatic tools are not mutually exclusive and might be better classified as "visuo-mathematical". For example, James Clerk Maxwell regarded Michael Faraday as "a mathematician of a very high order" (Maxwell, 1890b) because Faraday employed "visuo-mathematical" techniques. I believe that Krieger's system of classification would also benefit from highlighting physicists' use of constructive modelling tools. Nersessian's (1995) findings from her cognitive-historical studies (of Maxwell in particular) suggest that constructive modelling, which she defines as: "a dynamic reasoning process involving analogical and visual modelling and mental simulation to create models of the target problem," is "highly productive of solving problems and widely employed by experts in physics." (Nersessian, 1995, p.207 & 222).

Question **2c** of the on-line questionnaire asked: *"Where you do have difficulty [getting a mental picture of the various kinds of physical processes involved in your research] how do you overcome this?"* Questionnaire data reveal a spectrum of visualization techniques from across the physics community, although individual physicists tended to mention using only one or two techniques.[61] Examples provided by respondents included (re-coded and presented here in order of prevalence): the use of models/simplification/limiting case analysis; drawing/sketching ephemeral ideas; looking for analogies elsewhere in science; using computers as visualization tools; constructing mental pictures of mathematical structures (as opposed to visualizing the physical entities to which they supposedly refer) i.e. seeking visualizability rather than visualization; doing some background reading or asking a colleague/expert; trying to explain it to someone else; thinking about something completely different/having a change of scenery; achieving an altered state of consciousness through sleep deprivation or smoking cannabis; etc.

As with visualization difficulties, visualization techniques employed by an individual often depended on their innate abilities, training, resources and environment. Many physicists said that they work through their visualization difficulties by discussing it with colleagues or supervisors because the challenge of communicating their ideas verbally, symbolically, graphically, or mathematically often enabled them to look at the problem from a new perspective, thus producing fresh insights. This is in line with the views of physicists David Bohm and David F. Peat who tell us that:

> "... communication is as essential for the creative act as is perception through the mind. Indeed, within this context, perception and communication are inseparably related, so that creation arises as much in the flow of ideas between people as in the understanding of the individual alone." (Bohm & Peat, 1987, p.63)

There is also considerable evidence from recent studies in the field of cognitive psychology to suggest that peer collaboration is important to problem solving and that verbalising one's thoughts enhances one's problem solving abilities (cf. Chi, 1996). This notion can in fact be traced back to the educational psychologist Lev Vygotsky's research on the importance of 'private speech' on cognitive development (Vygotsky, 1934). Vygotsky held that "private speech" enables children (and to a certain extent adults) to consciously direct their thought processes.[62]

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[61] 60% of respondents mentioned using one visualization technique, 24% of respondents mentioned using two visualization techniques.

[62] As Norman has commented: "People operate as a type of distributed intelligence, where much of our intelligent behaviour results from the interaction of mental processes with the objects and constraints of the world and where much behaviour takes place through a cooperative process with others."(Norman, 1993, p.146)

Many questionnaire respondents said they overcome their visualization difficulties in private, by reading journal articles or allowing their mind to process the information 'off-line' by having a change of scenery e.g. taking a walk outdoors, etc. After studying the infamous insights of Archimedes, Poincaré et al., René Taton wrote in 1962 that "the study of various types of invention and discovery has shown us that after a long effort of reflection and research a discovery will suddenly flash into the mind of the research worker by means of a sudden illumination, the so-called Geistesblizt.' (Taton, 1962, p.74). Taton wrote that,

> "this flash of thought... does not generally appear during periods of assiduous work, but rather during those of rest or relaxation... Maturing slowly as a result of previous effort and the work of the subconscious, a discovery till suddenly appear at such times as the investigator's mind did not seem to be dealing with it." (ibid. p.28-29)

There are many reasons why a physicist may work through their visualization difficulties on their own rather than seeking help from others. For example they may have little access to expert opinion, particularly if they themselves are at the forefront of the research. Alternatively, working alone may be a personality trait. As detailed by Feist & Gorman (1998, p.26-27), there is some evidence to suggest that a scientist's personality influences theory creation, acceptance, and orientation, although no clear-cut causal relationship has been shown to exist between personality and scientific behaviour.

The availability of practical resources is also a key factor. For example, if physicists have equipment or computer software at their disposal, they can attempt to confirm a theory through carrying out an experiment in the laboratory or through numerical modelling. [63] With regard to innate abilities and training, physicists who have good visuo-spatial abilities and are mathematically inclined, often construct mental pictures of mathematical structures, rather than visualising the physical entities to which these structures supposedly refer; while physicists who are not mathematically inclined often take a mechanistic approach, using visual analogies as scaffolding around which to build their understanding.

Approximately 30 respondents mentioned using sketches to overcome their difficulties of getting a mental picture of the physical processes involved in their research. There appear to be parallels between my findings on the visualisation techniques used by **physicists**, and Suwa, Gero, and Purcell's (1999) findings on the techniques used by **designers**. Suwa et al (1999) tell us that:

[63] e.g. **Phys_225**, an undergraduate physicist from Zimbabwe remarked: "The University with which i am doing my degree is underprivileged and the availability of resources is not always at our disposal."

> "Design sketches serve as a medium through which a designer makes visual/spatial reasoning; a designer externalises newly formed but still vague ideas in the form of less rigid and ambiguous depictions on paper. By inspecting those externalised ideas, the designer finds useful clues to refine them, which motivates him or her to draw again." (Suwa, Gero, & Purcell, 1999 web ref.)

3.4 Achieving conceptual fluency:

According to Descartes, conceiving and imagining are quite distinct. What we cannot imagine we might well conceive. Descartes' famous example was the chiliagon, a regular 1000-sided figure, indistinguishable in imagination from a regular 999-dised figure. According to Dennett:

> "Conceiving of something complex – whether an abstract mathematical structure, a complicated physical process, or a system of rules or moves like chess or a grammar – is a matter of learning your way round in a 'space' you must construct in your mind. Only by actively exploring such spaces can we become familiar with them to the point of conceptual fluency, which is the point at which the Cartesian illusion is engendered of an act of direct conception. Getting to that level of fluency can be very difficult." (Dennett, 1990, p299)

As I mentioned in chapter 1, Einstein was a visual and kinaesthetic thinker. Was Einstein's inability to achieve a sufficiently high level of 'conceptual fluency' in certain areas of physics a contributing factor in his inability to formulate a unified field theory? As Miller (1984, p.246) puts it:

> "Could it have been that Einstein never achieved his lifelong goal of the highest level in his hierarchy – the unified field theory – because of limitations on his mode of visual thinking? Such a highly-placed theory would be impoverished in concepts because its concepts would be at best indirectly connected with objects from the world of perceptions. Perhaps this was the reason why there were no more thought experiments like the ones of 1895 and 1907."

This issue of seeking 'visualisability' rather than 'visualisation' is highlighted by two questionnaire respondents in particular. The first respondent, **Phys_160**, (a 52 year old, male reader in theoretical physics) finds it quite difficult to get a mental picture of the physical processes involved in his research: "Because the basic entities with which quantum theory (and to a lesser extent relativity) deal are not directly observable, and behave in ways for which everyday experience provides no reliable analogy." He said he overcomes these difficulties: "1) By learning to manipulate mathematical symbols without visualization 2) By constructing mental pictures of mathematical structures, which is not the same thing as visualizing the physical entities to which they supposedly refer." The second respondent, **Phys_214**, (a 24 year old, male PhD student) also finds it quite difficult to get a mental picture of the physical processes involved in his research, because he deals with "quantum phenomena that do not always have classical counterparts." To overcome these difficulties he says he must: "Raise concepts to a higher level of abstraction so that I visualise the form of the theory rather than the form of the objects involved." Thus, my questionnaire data suggests that in certain areas of quantum physics, the ability to abandon an attachment to concepts drawn from the world of perceptions may be necessary for scientific progress. In sections 3.5 & 3.6 I present data from my on-line questionnaire and my interview with Prof. Berry concerning the way in which different modes of thought predominate with different individuals.

3.5 Different modes of thought predominate with different individuals.

The influential 20th century philosopher-psychologist-physiologist William James, who coined the term, "stream of consciousness," believed it was possible for different modes of thought to predominate with different individuals: "With one, visual images predominate, with others, tactile." (James, 1971, pp. 68, 69). However, many fine-gained historical case studies of renowned scientists suggest that they employed hybridised forms of scientific reasoning, often combining what might be referred to as pictorial, visual, diagrammatic, graphical, symbolic or mathematical forms of reasoning, depending on the context and objectives. For example, Matt Ridley (author of the best selling popular science book, *Genome,* 1999) marvels at Francis Crick's ability to think in three modes of thought at once. In a recent article, Ridley writes: "I have never met a mind like his. He could think in three ways at once: in words, in algebra and in visual images. It was the sheer power of his imagination that dominated molecular biology in the 1950s and 1960s and neuroscience in the 1980s." (Ridley, 2004, web ref.).

Several respondents remarked upon a dichotomy in modes of thought exhibited by physicists within and across sub-branches of physics. For example, **Phys_54** (a 40 year old lecturer in theoretical physics) remarked that he had:

> "noticed a big difference among mathematical physicists who deal with geometry and who 'think in pictures' (like myself), and those who deal with algebra (relevant for a lot of quantum field theory) and who just think in terms of various sets of algebraic relations as being the most fundamental thing. One gets interesting differences between people in terms of the sort of mathematics they like to work with."

This anecdotal evidence is supported by the findings of cognitive psychologists. Klahr and Dunbar's (1988) *Big Track* experiments identified two distinct cognitive styles among their participants: theorists who spent more time searching hypothesis space, and experimenters who spent more time in an experiment space. Klahr tells us that:

> "Differences in preference between experiment-driven and theory-driven strategies have been noticed in other laboratory studies (Okada, 1994; Okada and Simon, 1995). Studies based on historical approaches can be interpreted in terms of the balance between hypothesis space search and experiment-space search. For example in most histories of Faraday's discovery of induction of electricity by magnets, much emphasis has been placed on the influence of Ampère's theory of magnetism on Faraday's thought, but a strong case can be made (Gooding, 1990) that Faraday's primary search strategy was to focus on experiment-space search, yielding a discovery path that was driven largely by phenomena rather than theory. (See Klahr and Simon, 1999, for further comparisons between laboratory and historical studies of the discovery process)." (Klahr, 2000, p.206)

Many respondents held the view that their reliance on "physical insight and analogies" probably stemmed from them being "weaker mathematician[s]." Of course, this places them in good company - Einstein also relied on physical insight gained through employing thought experiments and analogies and was not a mathematician of high calibre. In fact it is said that Einstein often ordered his mathematics delivered from his friend Marcel Grossman (cf. Miller, 2000, p.213).

Phys_57 (a 37 year old, senior lecturer in coastal engineering) said in the additional comments section of the questionnaire that he would be: "interested to find out if those who consider themselves stronger in mathematical/theoretical development need to use visualisation or analogies at all. I suspect that as a weaker mathematician I need to rely on 'physical insight' and analogies more than others. Certainly I find it difficult to develop theory if I cannot first visualise the processes." This reliance on physical insight and analogies was also shared by my case study respondent who (like Phys_57) also considered himself to be a weaker mathematician. (This is discussed in chapters 7 and 8).

Phys_50 (a 50 year old, professor of experimental physics) said he "never" finds it difficult to get a mental picture of the physical processes involved in his research: "Because I think with mental images much more than I do with language or with mathematics." He went on to say that he has been: "engaged in controversy with philosophers, who in my view mistakenly think that language is important or essential in thinking and in science. E.g. 'logical positivism is the position that science consists of *statements* that . . .' [end quotation]". As Nersessian points out:

"What is wrong with the positivist formulations from the perspective of learning is that even if the precise formulation of a theory were linguistic/formulaic in format, this does not imply that the kinds of representations humans employ in thinking with the theory are primarily of this format or that reasoning during problem solving is solely carrying out logical operations on linguistic/formulaic objects." (Nersessian, 1995, p.222)

Richard Feynman provides a nice anecdote to illustrate the fact that thoughts can be visual as well as verbal. He recounts (Feynman, 1988, p.54) how:

"One time, we were discussing something – we must have been eleven or twelve at the time – and I said, "But thinking is nothing but talking to yourself."

"Oh yeah?" Bennie said. "Do you know the crazy shape of the crankshaft in a car?"

"Yeah, what of it?"

"Good. Now tell me: how did you describe it when you were talking to yourself?"

So I learned from Bennie that thoughts can be visual as well as verbal."

Considerable uncertainty remains regarding the nature and form of scientific thinking (e.g. Knauff & Johnson-Laird, 2002, suggest that visual imagery can actually impede reasoning). Both the language-based, syntactical view [64] of scientific theories, and the model-based, semantic view of scientific theories[65] have merit. Progress in this research area is hampered by the complexity of the issue: there are difficulties operationalising terms, distinguishing what it means to represent, resemble, image, visualise, etc. as well as difficulties interpreting the psychological and neurological data on language processing, cognitive architectures, perception, vision, etc. Thinking is usually categorised according to coarse divisions such as: words or images; verbal or mathematical descriptions; iconic (i.e. pictures, diagrams and metaphors) or symbolic (i.e. mathematical) representations, etc. However, a pictorial/ mathematical or pictorial/algebraic classification is too coarse to handle the concept of a graphical language, which combines aspects of both. For example, **Phys_198,** (a 32 year old, male, lecturer in physics, whose research interests include the study of matter antimatter asymmetries in the Universe (CP violation) through accelerator based experiments) claimed to *"never"* find it difficult to get a mental picture of the physical processes involved in his research, because: "High Energy physics has developed

[64] As Morgan & Morrison (1999, p. 1) explain, in the syntactic view, "the theory itself was explicated in terms of its logical form with the meanings or semantics given by an additional set of definitions, the correspondence rules. That is to say, although the theory consisted of a set of sentences expressed in a particular language, the axioms syntactically describable. Hence, without correspondence rules, one could think of the theory itself as uninterpreted."

[65] For discussions on the semantic view see: Johnson-Laird, 1983; Gentner, 1983; Nersesian, 1999; Campbell, 1920; Braithwaite 1953, 1954; Black, 1962; Hesse, 1966, 1970; Harré, R., 1960, 1982, 1988, 1990; Kuhn, 1970; Morgan & Morrison, 1999; Hartman, 1999; Hughes, 1999; Winsberg, 1999; Cartright, 1983 (pp.133-134), 1999; Cartright, Suarez and Shomar, 1995; Pickering, 1989; Gooding, 1981, 1986, 1990, 1992; Giere, 1998, Suppes, 1961, 1967; Suppe, 1977; van Fraassen, 1980.

a very powerful graphics language that ties in with the math. This helps to create the mental picture." Rather than attempting to classify a graphic language according to a pictorial/mathematical system of classification, could one adapt Goodman's (1976) system of classification (discussed in section 1.17) such that a graphical language is regarded as a notational system that is *dense* but *attenuated*? [66]

Although it is notoriously difficult to operationalise terms and categorise thinking, it is widely accepted that individuals have preferred modes of thought. As we saw in chapter 2 and previously in this chapter, for many physicists, there is a sharp divide between theoreticians and experimentalists. For example, **Phys_198** remarked that visualization difficulties he occasionally experiences are due mainly to the fact that: "Theoreticians generally don't present their work in a suitably 'visual' sense. It can be hard to visualise equations into their physical meaning without adequate diagrams etc." This prompted several questions to my mind: Could all of physics benefit from theoreticians presenting their work in a more visual sense? Or is that simply not practical because many researchers are skilled at constructing mental pictures of mathematical structures and prefer this approach? Are computer visualisations the best alternative visual aid? Bearing in mind that computer simulations fall short when trying to imagine new laws, because one needs the laws to put into the computer in order to run simulations. Should more of an effort be made to teach physics, mathematics and engineering students to 'see'? Could computers be successfully employed in this educational endeavour? Barbara White's **ThinkerTools** research group, which develops computer bases learning environments would seem to suggest so. (cf. White, 1993; White, Shimoda, & Frederiksen, 1999). I pursued these questions in my follow-up e-mail exchanges with a select sample of physicists and also in my semi-structured interview with Prof. Berry. This is discussed in section 3.6 below.

3.6 Presenting Research to Physicists Possessing Different Modes of Thought

In Prof. Berry's view, having <u>both</u> pictorial/diagrammatic and analytical/algebraic modes of thought was "very useful." In our semi-structured interview, I asked if he thought it was "an area that might need developing, in that not all theoretical physicists operate on both levels." Prof. Berry was pensive for a moment on this question. He then said: "Well, I find

[66] I considered applying Goodman's system of classification to my examples of analogy (discussed in chapter 2). However, I found that my data was not very well suited to this system and that it was more revealing to apply a less rigorous system of classification, drawing on the work of Gentner (1989) and Boon (2005) in particular.

it advantageous to have both and I think it's a strength. But as I said, people I respect, who have made enormous contributions, don't think visually – so it hasn't affected them." I continued to press the issue, asking: "From the point of view of interdisciplinary work. If you have people writing in a journal and other people reading it, and obviously if you think in a different way, it's more difficult to -". Prof. Berry interrupted, saying: "Yes, but then you put both. I mean I do. My scientific papers are full of equations and pictures." This may be part of Prof. Berry's success. As he utilises both modes of thought himself, he presents his work both algebraically and pictorially. As a result, it is likely that Prof. Berry's papers are understood by a larger population of theoretical physicists than if he presented his work in just one mode of thought.

Similarly, in chapters 7 & 8 we see that Dr. Lawson used pictorial and algebraic modes of thought in his scientific papers and conference talks in order to bridge conceptual and 'linguistic' divides between experts coming from sub-disciplines related to particle physics. In Dr. Lawson's case, physical and pictorial analogies were presented alongside abstract mathematical equations. I also raised this issue in follow-up email exchanges with some physicists who had provided interesting comments to related issues when responding to the on-line questionnaire. I asked:

> *"In your opinion, could all of physics benefit from theoreticians presenting their work in a more visualisable form? [67]Or is that simply not practical because many theorists are skilled at 'constructing mental pictures of mathematical structures' and prefer this approach?"*

Phys_57 certainly thought physics could benefit from theoreticians presenting their work in a suitable visual sense: it was vital for him to have a mental or physical visualization in order to understand the theory. As he put it in his follow-up reply:

> "Yes: I have great difficulty understanding any physics/ physical process unless I can interpret that process mentally. For me, mental or physical visualization is essential to my being able to interpret theory and investigate the implications of that theory." (Phys_57b)

Phys_54 said that one must be tolerant of different approaches because what works in one area of physics might not work in another. However he felt that physicists who normally work entirely with mathematical structures should learn to relate the arcane mathematics to observable quantities in the real world for the benefit of everyone. In his words:

> "It is a question of who they are presenting their work to. Certainly if it is to the general public, or even to graduate students, then visual presentations help, even if it is

[67] [With hindsight, 'visual sense' would have been better than 'visualisable' because, as mentioned previously, there is a subtle philosophical distinction between 'visualization' and 'visualizability'.]

> at the level of 'constructing mental pictures of mathematical structures'. The problem nowadays is over-specialization. There are many people who work on arcane areas, where they do just work with mathematical structures, without having to worry about physical applications. I believe all these approaches have their uses and importance, and what works in one part of theoretical physics won't necessarily work in another part; we have to be tolerant of different approaches, rather thinking that our own individual niches hold everything. Just whenever anyone gets to the point where they have to relate the mathematics to something which one considers to be an observable quantity in the real world, then it helps to have simple visual models, since we are supposed to be talking about the real world after all. That's a skill people should learn." (Phys_54b)

This emphasis on being tolerant of different approaches echoed Prof. Berry's views. Having both modes can be advantageous for oneself and for others who value reading papers containing both modes of thought, but many acclaimed individuals have made great advances using non-visual and non-physical modes of thought when conceptualising and communicating their work.

Phys_160, (a 52 year old, male, Reader in Theoretical Physics) urged caution in his reply to my follow-up queries, saying:

> "I think that asking theoreticians to present their work in a visual form would be both impractical and dangerous, but perhaps not for the reason you suggest. Here are some points that occur to me:
>
> a) I am by no means as skilled at constructing these mental pictures as I would like to be. To the extent that I can do it, I find that the pictures build themselves while I am poring over equations and trying to grasp what they mean. It would be nice to have a conscious strategy for accelerating this process, but I don't think I could formulate one.
>
> b) These mental pictures are mainly very personal. It would be hard to explain to someone else what the picture I have looks like, and I doubt whether they would find it helpful if I did.
>
> c) They are also quite vague. Occasionally, I try to help myself by drawing them on paper, and I usually don't recognise the result once I have done it.
>
> d) They are also incomplete. They help me to preserve a sense of how various ideas fit together, but they don't always give a detailed representation of what those ideas actually are. Often, they are a sort of mnemonic – like the knot in a handkerchief, which jogs the memory, but doesn't tell you explicitly what you were supposed to remember. This is the dangerous part. Even if I could explain to someone else what my picture looks like, and

what it means to me, the other person might be seriously misled by not seeing where my picture fails.

e) It is notoriously difficult to get theoretical physicists to agree even on such relatively straightforward matters as notation and sign conventions. It would surely be much more difficult to get them to agree on any standard ways of visualizing - and one would need common standards if this were to be of any practical use. The way of expressing a given idea that seems most transparent to one person does not necessarily seem so to another. I am inclined to think that this reflects not only the ways in which different individuals think, but also the routes by which different individuals have arrived at their understandings of the same idea." (Phys_160b)

Phys_160's comments in (d) resonate with the use of analogies in science: Analogies are incomplete associations; they can be extremely useful as heuristic devices when solving problems via constructive modelling; creative misunderstanding in the use of analogy can prove productive and enlightening, however other forms of misunderstandings, like over-extending the analogy or confusing the map with the territory, can be dangerous.

In follow-up exchanges with a selection of questionnaire respondents I also asked:

"Are computer visualisations the best alternative visual aid? Or could physicists learn specific visualization skills (what some respondents have called "tricks") that would assist them in their attempts to "visualize equations into their physical meaning"? Because as you [/ one respondent] said, when "trying to imagine NEW laws - computer simulations won't work because one needs the laws to put into the computer to simulate."

Phys_160 makes several interesting points in his reply to these questions. Firstly, he points out that we must acknowledge that there are different types of visualizations. Secondly, there exist many visualization tools for dealing with exact representations. Thirdly, the type of visualizations implied in my questions are not exact, however, and computer simulations of these merely suggest the structure one is trying to understand. Fourthly, that the suggestiveness of these images cannot be predicted or controlled by the image creator, because physicists will interpret them according to their previous training, their own research focus, perhaps even associating the mathematical creations with geographical features of their surrounding landscape. In **Phys_160's** words:

"I would think that this depends very much on what it is that one is trying to visualize. Of course, we do have various means of visualizing certain things: graphs, histograms, Venn diagrams, Feynman diagrams, ...Sometimes, computer graphics can extend the power of what we can already do on paper, for example by making 3-d images freely rotatable or by animation. I think that visual aids or mental tricks work well when it is possible to give rules which say precisely what each element of an image represents. This means that the image is an exact representation of some mathematical idea (or one that could in principle be exact - for example, one can get a good enough idea of what sin(x) means from a rough sketch of the curve, without plotting all the points to 10 figure accuracy, but this works only because we know in principle how the rough sketch might be transformed into a precise graph.). However, the visualizations that I think you are more interested in are not exact, even in principle. They can at best only be suggestive of the structure one is trying to understand. Then one has the problem that a given image will suggest different things to different individuals, depending on many factors that the image creator cannot control. For example, it happens that various mathematical ideas are linked in my mind with geographical features of the town in which I grew up (which happens to be close to your university). Probably, this is for no better reason than that I happened to remember some event in the past at the time I was working on some particular problem. These serendipitous associations are not the mental pictures we are mainly talking about, but they illustrate the personal nature of imagery as a whole." (Phys_160b)

The concluding remarks of **Phys_160** touch on the "distributive cognition perspective" which "contends that the environment provides a rich structure that supports problem solving." (Nersessian, 2005, pp.27-28)

Phys_57 believed that the models underlying these computer-generated visualizations are useful at providing falsifiable outcomes or in helping users to identify patterns amid complex calculations. However, computer-generated visualizations still fall short when one is trying to imagine non-visualizable entities like higher dimensionality. As Phys_57 remarked:

"No & Yes. I agree with the above phys 115 that models often represent a sometimes correct but irrelevant view of our world...(ie wrong assumptions, but valid calculations) but they are useful for providing 'testable' (falsifiable) outcomes or presenting complex calculations in which patterns are evident. However, sometimes it is just possible to imagine concepts such as higher dimensionality that cannot be represented even by a 3D image…In any case some sort of visualisation would always be useful to me." (Phys_57b)

In response to the same question **Phys_54** said:

"No; while computer visualisations are fine for extending existing physics to new regimes, they are not necessarily the best visual aid when you are trying to develop something which requires a new identification of the relationship between observed quantities and mathematical symbols." (Phys_54b)

Phys_54's research often involves revolutionary new ideas in cosmology, general relativity and quantum gravity, where computer visualizations are not always useful. So what methods does **Phys_54** use when trying to imagine new laws? Following in the footsteps of Albert Einstein, he often uses thought experiments.

3.7 The Value of Thought Experiments

Phys_54 said that he finds **thought experiments** very useful when talking about conditions that are impossible to reproduce in the laboratory. He explains:

> "In trying to do something really new, I go for that old method of Einstein, the Gedankenexperiment. I try to picture something visually in terms of things I believe correspond to measurements, and then think my way through it. As it happens, you have caught me at just the time when I am trying to write down a new model cosmology which if correct would change a fundamental paradigm: get rid of dark energy as an explanation for 'cosmic acceleration' and replace it by a complicated hierarchical fractal geometry, as allowed by Einstein's equations.... While the idea that one can explain cosmological parameters by inhomogeneous geometry is something that dozens of other people have pursued, they have been concentrating on mathematical techniques and theorems. I am trying to do things quite differently, going very much outside the box as far as the perturbative mathematical techniques are concerned, by thinking carefully about what it is that is actually measured and giving a solution which identifies various cosmic clocks in a different way to convention, but consistently with general relativity. The important section of the paper I am now writing begins with a Gedanken experiment. I...would be happy to send you a copy." (Phys_54b)

Phys_54's reference to changing a fundamental paradigm ties in with Kuhn's (1981) views on thought experiments: essential analytic tools deployed during crisis, enabling the scientist to use pre-existing knowledge to bring about a conceptual change or "paradigm shift". (See also Sorensen, 1992; Brown,1991). **Phys_54** uses thought experiments as conceptual tools of exploration in his private conceptualisations and also when presenting his ideas to his peers in formal contexts. **Phys_54** introduces his Gedankenexperiment in section 2.1 of his scientific paper in the following way:

> "To introduce a conceptual framework and appropriate terminology to deal with the possibility that we might live inside a density perturbation, let us conduct a simple Gedankenexperiment. Take an initial spatial hypersurface corresponding to the end of the inflationary epoch. Onto this hypersurface randomly scatter small spheres of all proper sizes, allowing spheres to fall inside other spheres, from some smallest scale, up to some largest scale β. By this means larger spheres will naturally contain all smaller spheres, according to a distribution which could in principle be calculated. The fact that there exists a largest scale,

> β, of perturbations is simply due to the fact that inflation ends, so there must be a cut–off to the spectrum of perturbations at some upper bound…"

Phys_54 had not yet finished his paper in 2005. Proving his theory to the satisfaction of his peers involved, "recalculating all the standard things about the early radiation dominated epoch, before the universe was a few hundred thousand years old. It takes a while!" (Phys_54d) In a subsequent e-mail I then asked **Phys_54:**

> "In your experience how common are Gedankenexperiments in the journal papers in your area? Is there a tendency for them to appear in certain journals in particular? An eminent British physicist I spoke to last year said that he tends to avoid Physical Review Letters because they censor his creative use of language, even though his 'creative' terms have been widely adopted by his peers. I was just wondering if you've come across anything similar in your area."

I was referring to Prof. Berry's experiences with Physical Review Letters censorship of two terms he coined "diabolical point" and "quantum chaology" (discussed in section 5.8). **Phys_54** said:

> "…thought experiments are a useful construct in exploring the limits of our conceptual understanding. I wouldn't say that thought experiments are more likely to be in certain journals than others, but that they are more likely in areas of fundamental physics for the reasons above, and any journal selection effect is a consequence of that. It is true that Physical Review do not like people coining new terms, and they do not like jokes, but otherwise it is just as likely to find them there as anywhere else." (Phys_54e) [68]

Phys_54 provided me with some examples of thought experiments used by his peers. These are summarised in appendix 3, section A3.2. **Phys_54** concluded his e-mail by saying that: "Basically thought experiments are a way of taking physical principles and understanding to situations beyond our usual experience, and in the cases above to realms where there is no way that we know of conducting the experiments in reality, at least in the foreseeable future." **(Phys_54e)** Thus, the type of thought experiment performed by **Phys_54** would be classified as "truly imagined" in Gilbert & Reiner's (2000) theoretical framework, i.e. a construct of the imagination only and thus impossible to conduct in a lab. As distinct from "merely imagined" TE's, i.e. an experiment which could have been carried out in a lab, but for some reason or other was not.

[68] Phys_54 added: "Phys. Rev. Letters is a hard one as they restrict you to four pages; it's not easy to get a thought experiment over in such a limited length. In fact, anything radically new is very difficult to get across in 4 pages; I sent gr-qc/0503099 to Phys. Rev. Lett. originally but they rejected it as the referees didn't understand what I am trying to do. That's why I'm going for a very long paper now." (Phys_54e).

3.7.1 Quantitative data on the degree to which questionnaire respondents visualise different kinds of experiments.

In the early stages of my research, I did actually intend to investigate the extent to which physicists employ thought experiments in their work. However, the pilot questionnaire showed that many physicists were put off by the questions regarding their use of 'thought experiments' in their work. Many physicists felt that the term 'thought experiment' sounded either too profound or too much like armchair philosophy to be identified with what they did in their work. Thus, the *Thought Experiments* section was removed, and four (tick box) questions on "visualising experiments" were added to the *Visualization* section of the questionnaire, using Gilbert & Reiner's (2000) theoretical framework as a guide. Question 2d read:

"Q2d. How often do you visualise experiments which are:

(i) *then physically performed;*

(ii) *too expensive or technically difficult to physically perform;*

(iii) *physically performable, but doing so would offer no further insight*

(iv) *impossible to physically perform.*

The quantitative data relating to these questions is plotted in figures A3.1 to A3.4 in Appendix 3, section A3.3. As shown in table 3.2 on the next page, there was a large number of missing responses and large standard deviations. This indicates that there was considerable uncertainty surrounding this 4-part question.

7-point scale from 1/never to 7/always	Visualise experiments which are then physically performed	Visualise experiments which are too expensive or technically difficult to physically perform	Visualise experiments which are physically performable but to do so would offer no further insight	Visualise experiments which are impossible to physically perform
N Valid	214.0	212.0	206.0	212.0
N Missing	11.0	13.0	19.0	13.0
Mean	4.1	3.8	2.7	3.2
Median	4.0	4.0	2.0	2.0
Mode	4.0	5.0	1.0	2.0
Std. Deviation	2.0	1.9	1.6	2.1

Table 3.3 Statistics from Q2d on the extent to which respondents' visualise experiments.

As there was no qualitative question to follow it up, and the remaining questions generated an extremely large amount of qualitative and quantitative data, I chose not to explore thought experiments as a central research question. However, the issue subsequently arose in my e-mail conversations with **Phys_54**, concerning visualization techniques. Thus, for the purpose of thoroughness and clarity I have included it here.

Some respondents felt that the questionnaire was tailored towards experimentalists rather than theorists and consequently theoretical and computational physicists may be unable to respond to the questions concerning the extent to which they visualise experiments.[69] For example, **Phys_177** (a 24 year old, PhD student, whose research interests include, quantum communication and information theory) said in the additional comments section, that the questionnaire: "seems a bit directed toward experimental physics. some theoretical or computational physicists may never imagine experiments...you could argue that is not physics though i suppose..." It is unclear whether **Phys_177** is implying that <u>imagining experiments</u> is not 'physics', or that <u>computational physics</u> is not 'physics'. If the former: surely every experiment performed, was first imagined in some considerable detail when designing the experimental set-up and procedure. As P.B. Medawar once said (1969, p57):

> "For an experimentalist the most exciting and pleasing act in science is thinking up or thinking out an experiment which provides a really searching test of a hypothesis. We recognise the intuitive element in such a process when we speak of experimental flair or insight, but here too no one word in common speech stands for everything it should convey."

Similarly, Gooding notes that, "Faraday recognised a connection between experimenting, representing & theorising," (Gooding, 1989, p.209) as did other great physicists like Richard Feynman and John Bardeen. Thus, **Phys_177** was probably suggesting that computational physics is not physics. The reality status of computer simulations is discussed in section 4.6.4.

3.8 Learning to See.

As mentioned in section 0.2, Nersessian believes that "we will be more successful at training students to think scientifically if they are taught, explicitly, how to engage in the modelling practices of those with expertise in physics." (Nersessian, 1995, pp204, 205). I believe that modelling practices are often founded on the notion of 'learning to see'. Mathematician and educator, Walter Whiteley (1992, web ref) highlights the importance of teaching students to see like a mathematician and underscores the value of computer software packages [70] as educational tools. In Whiteley's experience:

> "New computer tools, play with objects and images, and guided practice can change how students 'see' both external visuals and images in their mind's eye. The shift from simple images to insight is not a matter of luck it is a matter of learning... There are levels of visual performance, of seeing, thinking and communicating, just like

[69] my own degree in experimental physics may have influenced my focus in the questionnaire.
[70] Examples of software packages for teaching school geometry, mentioned by Whiteley are Cabri Geometrie, Geometers SketckPad and Cinderella.

there are levels of performance in algebra. These are skills to be understood, shared, practiced and valued in the mathematics classroom and in assessment." (Whiteley, 1992, p3, web ref.).

Whiteley outlines three steps towards teaching students to see like mathematicians:

1. A first step is an evolving awareness of how visuals are or could be used, and an explicit encouragement of their used.
2. A second step is paying attention to when students don't see what we see, seeking those occasions out and exploring them.
3. A third step is developing and sharing diverse examples, and diverse ways to see individual examples, along with tools which let students experience what we are seeing." (ibid.)

According to Chandrasekran & Narayanan (1992, p.30): "Prior exposure [to diagrams and other kinds of images] can lead to perceptual fluency in recognition and classification." As will be discussed in chapter 4, a majority of respondents believed that computer simulations *"definitely have"* helped strengthen physicists' visualization capabilities both in the respondent's *own research area* and *in physics in general.* But aside from the use of computer simulations, how do physicists learn to see the unseen? Are the specific visualization techniques mentioned in previous sections formally taught to physics students? I sought answers to this question in follow-up email exchanges with questionnaire respondents who had specifically referred to their education impacting on their visualisation abilities.

For example, **Phys_27** is a 25 year old, PhD student, whose research interests include: "Chemical vapour deposition growth of patterned arrays carbon nanotubes for interconnect and sensor applications." He rarely (i.e. 3/7 on the 7 point scale) finds it difficult to get a mental picture of the physical processes involved in his research because, as he put it: "Geometry and patterns I find very easy to visualise, too much organic steric chemistry as an undergrad." He said "Difficulties arise when I can't make analogies from my problem to such patterns of things I have a more intuitive knowledge. 'Let us begind [sic] by approximating a cow as a hollow shpere [sic] filled with milk.'" In a follow-up e-mail I asked **Phys_27**:

"You said that only occasionally do you find it difficult to get a mental picture of the physical processes involved in your research because you find 'geometry and patterns...very easy to visualise' as a result of studying, ' too much organic steric chemistry as an undergrad.' What visualization tools did you use when you were studying 'too much organic steric chemistry'? For example, did you use physical models, free-hand sketches, computer visualizations, etc.? I ask because I would like to explore whether formal training in specific visualization techniques might benefit physicists who experience visualization difficulties.

Phys_27 replied saying:

> "I have two methods to be very helpful for this kind of problem, first is to use a physical model (such as a ball and stick model for molecules) that I can actually touch and hold and rotate in my hands. The second is just good old concentration I find when I first approach some sort of visualisation task, it helps to sit somewhere quiet with my eyes closed, then start to visual the problem as some very simple such as two linked points or a simple euclidian shape and build it up from there in simple elements, much as you would if you were drawing a model with computer software." (Phys_27b)

In response to Q2 of the questionnaire, **Phys_91**, a 47 year old, Professor of Astrophysics whose research interests include "Astrophysics of stars and their circumstellar environments, and observational astronomy" said she very rarely (i.e. 2/7) finds it difficult to get a mental picture of the physical processes involve in her research because she has "a strong spatial imagination - have never had difficulty with maps, direction-finding, pattern recognition, can draw quite well. I sometimes get stumped by extreme instances of 3-D imagining." To overcome any visualisation difficulties she occasionally has she will, "Try to find simple limiting cases that I can visualise and build from there. Very occasionally I might think to resort to a concrete model (built from pencils, bits of paper etc..)"

Meanwhile, **Phys_2**, a 27 year old, PhD student, whose research interests include: "Vertical cavity devices, communications, high output devices" said he rarely (i.e. 3/7) finds it difficult to get a mental picture of the physical processes involved in his research because there is "No tangible evidence for what's going on." To overcome his difficulties he will, "try drawing a picture or similar visualisation." It would seem that such practices are rarely a part of **formal** education, as I discovered when I asked **Phys_2** and **Phys_91** the following question:

> *"Were your visualization abilities enhanced by any particular facet of your formal physics training? For example, another questionnaire respondent, Phys_27, said: 'Geometry and patterns I find very easy to visualise, too much organic steric chemistry as an undergrad'."*

Phys_2 replied: "Not that I can think of. I've always preferred the inclusion of drawings to aid with both understanding and explanation." **Phys_91** replied:

> "...not really. I think I mainly developed them as a child and early teenager. Formal physics training gives strong emphasis to mathematical reasoning. A good physics teacher will draw analogies but you won't find such enshrined in the curriculum! I have spotted and taught myself via analogies from time to time in my professional career."

For these three physicists, tacit or kinaesthetic knowledge - constructing physical models that one can see and touch and rotate in one's hands - is an important part of their visualizations. Thus in answer to Root-Bernstein's (1985, p.63) question: "to what extent visual imagination is dependent or independent of the kinaesthetic skills of drawing or modelling," in the case of these three physicists, it is highly dependent. However, the extent to which these important skills are formally taught is unclear. On the surface it appears that the skills of drawing or modelling are developed by the physicists themselves prior to or in parallel with their formal scientific education. Perhaps all physics students should be formally taught to generate analogies, build mental and physical models and (like some physics students and most engineering and architectural students) learn some basic drawing and drafting techniques to strengthen their tacit and visual skills.

3.9 Conclusions:

The primary aims were to investigate (i) the degree to which physicists experience **difficulty getting a mental picture of the physical processes** involved in their research; (ii) the primary **factors** perceived by respondents to account for these difficulties (iii) and the techniques used by respondents to overcome any difficulties they had. As shown in section 3.2, initial findings indicated that two thirds of respondents have difficulty getting a mental picture of the various kinds of physical process involved in their research, somewhere between *"1/never"* and *"3"* on a 7-point scale which runs from "1/never" to *"7/always"*. **Subject area** was the most significant factor in determining the degree to which physicists experience visualization difficulties in their research. Factors such as (ii) **innate abilities,** (iii) **training,** and (iv) **experience** were less significant factors in determining the degree to which physicists reported experiencing difficulties getting a mental picture of the various kinds of physical processes involved in their research. A complex web of inter-related factors surrounds this issue. For example two respondents may have undergone the same initial training (e.g. a degree in experimental physics) but chose to carry out doctoral work in different subject areas (e.g. quantum computing, geophysics, astrophysics, or biophysics). As these subject areas vary in their visual nature, respondents with similar innate abilities, training and experience may have different levels of difficulty visualizing things. With regard to **subject area**: in areas where classical physics predominates, physicists often employ mathematical, physical and pictorial analogies to gain insights. In highly theoretical areas, at the forefront of research, respondents often abandon attempts to form mental pictures of the physical processes involved in their research and instead raise concepts to higher levels of abstraction and visualise the form of the equations representing the objects under investigation. Thus, following the lead of Bohr and Heisenberg they search for "visualizability (visual images generated from scientific theories) and not visualization (visual images abstracted from phenomena we have witnessed in the world of perceptions." (Miller, 2000, p. 310). Certain areas like high-energy physics have developed a very powerful graphical language that fuses mathematical intuition with visual imagery. For many physicists, this helps to create the mental picture of the physical processes involved. The on-line questionnaire revealed a spectrum of visualization techniques from across the sub-cultures of the physics community. The most often cited techniques were the use of models, simplification and limiting case analysis, drawing and sketching, analogical reasoning, and the use of computer simulations. The latter two techniques are discussed in considerable depth in chapters 4, 5 & 6 as there were additional sections in the questionnaire covering these topics.

Though there were numerous examples given (cf. section 3.3), individual physicists tended to only mention one or two specific techniques that appeared to be affected by their: **innate** abilities (i.e. mathematical, visuo-spatial, technical, verbal, social etc.); their **training** (i.e. theoretical, experimental, mathematical; a preference for geometry or algebra; experience of dealing with complex geometries from undergraduate classes in e.g. steric chemistry); **resources** (i.e. availability of equipment, computer software, etc.); **environment** (e.g. they may gain inspiration from their *physical surroundings*, everything from what sits on their desk - a snickers bar, a cheese sandwich - to what they see when they look out their window -- a football stadium, a river; and/or they may gain inspiration from their *social surrounding*s if the have the opportunity to brainstorm their ideas with colleagues, advisors etc.)

Thus, it is clear that some physicists' still experience difficulties getting a mental picture of the various kind of physical processes involved in their research, but that a majority are successful at overcoming these difficulties through personal or communal strategies, e.g. by employing sketches, analogies or computer simulations or by raising the concepts to a higher level of abstraction and seeking visualizability rather than visualization. For many physicists, kinaesthetic skills of drawing and of physical modelling and reasoning by analogy are important aspects of their ability to visualise their subject matter. It is unclear to what extent these important skills are formally taught to physicists. Some physicists appear to develop these skills themselves prior to or in conjunction with their formal physics education. I suggest that all physics students should be formally taught to generate analogies, build mental and physical models and learn some basic drawing and drafting techniques (like those learned by some physics students and most engineering and architectural students) to strengthen their tacit and visual skills.

Chapter 4

On Physicists' Use Of Computer Simulations As Visualization Tools

"The purpose of computing is insight, not numbers."

"Machines should work. People should think."

Richard Hamming [71]

[71] Richard Hamming (1915-1998) was a mathematician whose work was influential in the fields of computing and telecommuications. He worked on the Manhattan project in 1945 and at Bell Labs 1946-1976. In 1947 he founded the **Association for Computing Machinery** (**ACM**) the world's first scientific and educational computing society.
Paraphrased from Wikepedia: The Free Encyclopedia.
URL: http://en.wikipedia.org/wiki/Hamming Accessed on 21-11-2005

4.0 Overview

This chapter presents data from section four of the on-line questionnaire on issues surrounding physicists' use of computer simulations as visualization tools. The following research questions are addressed:

- To what extent do these physicists employ computer simulations in their research?
- In what contexts do these physicists employ computer simulations?
- What reasons do these physicists provide for not using computer simulations in their research?
- Do these physicists believe that computer simulations have strengthened physicists' visualization capabilities (a) in their own research area? (b) in physics in general?
- What do these physicists believe are the possible disadvantages of employing computer simulations in research?
- Can computer simulations provide physicists with insights when conceptualising and communicating physics?

My findings show that computer simulations are used as visualization tools by questionnaire respondents in a variety of contexts. However, many respondents also use computer simulations for other purposes where visualizations are not the main goal but rather useful by-products. A majority of respondents believed that computer simulations have helped strengthen physicists' visualization capabilities both in their own research area and in physics in general. However, a small number of respondents held opposing views, believing that computer simulations may in fact weaken one's innate visualization abilities by acting as a mental crutch. When specifically asked about the disadvantages of employing computer simulations many respondents said that computer simulations suffer from the GIGO syndrome: if one puts **G**arbage **I**n on gets **G**arbage **O**ut. Following on from this, many respondents remarked that computer simulations could be misleading if misused by inexperienced researchers. For example, if no attempt is made to verify the computer model via physical and/or analytical means and the model becomes a black box whose inner workings are unknown. Many said that few (physical, pictorial, or mathematical) insights could be obtained when computer simulations became black boxes. This line of questioning suggested that many respondents take an instrumentalist view regarding the reality status of computer simulations. In many instances their primary function is as instruments to develop and test theories or design and build equipment.

4.1 Physicists' Use of Computer Simulations as Visualization Tools.

Question 4 of the on-line questionnaire asked: *In your research, do you ever use computer simulations to help you visualise things?"* Overall, there was a skew towards using computer simulations as visualization tools, with 48.2% of the sample selecting between **"5"** and **"7/all the time"** on the 7-point scale. The largest single group, 22.7% of the total, selected **"7/all the time".**

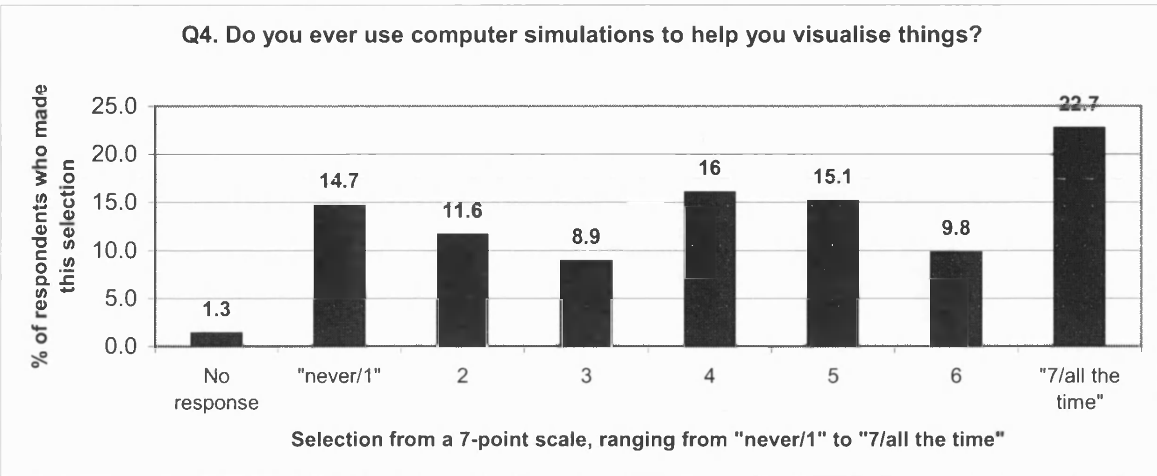

Figure 4.1: Chart showing extent to which respondents use computer simulations to visualise things.

Q4. In your research, do you ever use computer simulations to help you visualise things?								
7-point scale	**Frequency**	**Percent**	**Valid Percent**	**Cumulative Percent**	*Mode*	*Mean*	*Median*	*SD*
"never/1"	33	**14.7**	14.9	14.9				
2	26	**11.6**	11.7	26.6				
3	20	**8.9**	9.0	35.6				
4	36	**16**	16.2	51.8				
5	34	**15.1**	15.3	67.1				
6	22	**9.8**	9.9	77.0				
"7/all the time"	51	**22.7**	23.0	100				
Sub Total	222	**98.7**	100	100				
Missing Data	3	**1.3**						
Total	225	**100**	100	100	*7*	*4.3*	*4.0*	*2.1*

Table 4.1: Descriptive statistics for Q4 on use of computer simulations to visualise things.

The large standard deviation (of 2.1) may be the result of respondents not using computer simulations for the express purpose of visualization, but rather for calculating outcomes for which visualization is instead a useful by-product. This possibility is discussed in the following sections.

4.2 Instances in which respondents' use computer simulations:

Question 4b of the questionnaire asked: *"If so, can you please offer an example [of an instance in which you use computer simulations to help you visualise things]?"* The following examples offered by respondents have been selected with the intention of highlighting the **wide variety of contexts** in which respondents use computer simulations:

- "I simulate jets of gas from young stars - this helps enormously in understanding, particularly when coupled with animations of the results." **Phys_21** [72]
- "Use of hydro-dynamic simulation to look at the temperature and density evolution of a plasma irradiated by a laser pulse." **Phys_25** [73]
- "CFD [Computational Fluid Dynamics] visualisation of airflow around an aircraft showing shock waves and the TBL [Turbulent Boundary Layer]." **Phys_48** [74]
- "Erosion patterns due to waves on beach profiles." **Phys_57** [75]
- "Before we build a piece of hardware, we always make technical drawings of it, often with 3-D visualization. For every physical experiment performed, I tend to perform 3 computer experiments. Eg I have thermal models of systems, I can simulate many more configurations using a computer than in real life." **Phys_95** [76]
- "Pollution transportation transformation of particles in the atmosphere." **Phys_117** [77]
- "The detectors we design for high energy physics are heavily simulated already in the design phase. Without this we would simply not know if we built an instrument with a sufficient quality to do the job." **Phys_198** [78]
- "I use visualisation software to look at the atomic arrangements within crystal structures." **Phys_201** [79]

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[72] **Phys_21**, a 30 year old, male, lecturer, whose research interests include: "Interaction of gas flows around forming stars, and elements of how stars die."
[73] **Phys_25**, a 40 year old, male, senior lecturer, whose research interests include: x-ray scattering from dense plasmas as a way of finding out their properties e.g. electron-ion equilibration times.
[74] **Phys_48**, a 23 year old, male, research scientist, whose research interests include: "Research into application of optics, and Electro-optics i.e. detectors (SWIR, MWIR & LWIR) , lasers etc for industrial and military applications."
[75] **Phys_57**, a 37 year old, male, senior lecturer in coastal engineering and hydraulics.
[76] **Phys_95**, a 27 year old, male, PhD student, whose research interests include: "Building / testing meteorology sensors for Mars landers; Experimental physics; Fluid dynamics; Thermal analysis."
[77] **Phys_117**, a 35 year old, male, senior lecturer, whose research interests include: Global Climate; Particle-Cloud Physics and Chemistry. Air pollution; Techniques for sampling pollutants; Atmospheric Spectroscopy and Mass Spectrometric Techniques.
[78] **Phys_198**, a 32 year old, male, lecturer in physics, whose research interests include: Study of matter antimatter asymmetries in the Universe (CP violation) through accelerator based experiments.
[79] **Phys_201**, 36 year old, male, Lecturer, whose research interests include: High-pressure crystal structure studies of small-molecule systems.

As you can see, the examples range from visualizing complex interactions on nano-scales when working with crystals, to interactions on giga-scales when working with stars and galaxies. Simulations are particularly useful when dealing with things that are difficult or impossible to physically manipulate. Thus, they are also used to design equipment and to explore the evolution of systems when subjected to a variety of boundary conditions. This is discussed further in sections 4.5.1 to 4.5.4.

4.3 Reasons given for <u>not</u> using computer simulations in research.

Question **4c** of the on-line questionnaire asked respondents: *"If you don't use computer simulations in your research, is there a specific reason why you don't?"* Most physicists who made selections in the negative end of the scale when replying to question **4**, explained in **Q4c** that:

(i) they didn't need to use simulations as visualization tools because their work was easy to visualise;
(ii) they used simulations as number crunchers rather than visualization tools;
(iii) they did not have the time, funding or skills required to create simulations;
(iv) their work was observational, they dealt with "*real* data".

Two physicists were dismissive of the value of computer simulations, but for somewhat different reasons – one practical, the other philosophical. **Phys_200**, (a 60 year old, male, semi-retired, self employed, cement industry consultant with experience in "process engineering, process control etc. etc.") said he *"never"* uses computer simulations as visualisation tools because he does "not believe that modelling is sufficiently near to reality to be of value. It is only as good as the model used and most real life physical systems are much more complex than the model can handle in a reasonable amount of time." He said, "In my experience, the (mathematical) modellers have followed what I/we have done and not led us." **Phys_115** (a 51 year old, professor, involved in spectroscopy) said he *"never"* uses computer simulations as visualization tools because of a, "Distrust of pseudo reality." When questioned about the possible disadvantages of employing computer simulations, in question 4f, he said one disadvantage was the, "Promotion of a cartoon view of reality". In his view, "Vision is only one of the ways in which we know the world. Its dominance at present is pedagogical rather than fundamental." The reality status of computer simulations (and models in general) is discussed further in section 4.6 when data arising from Q4f is presented. First, I will present data from Q4d, on whether respondents believed computer simulations have strengthened physicists' visualisation capabilities.

4.4 Quantitative Data On The Extent to Which Computer Simulations Are Thought To Have Strengthened Physicists' Visualization Capabilities

There were two parts to question 4d of the on-line questionnaire, intended to draw on physicists' personal experiences of using computer simulations as visualization tools and their experiences of others using them. It asked: ***Q4d.*** *Do you think that computer simulations have strengthened physicists' visualization capabilities (i) in your own research area (ii) in physics in general?"* As figures 4.2 and 4.3 on the next pages indicate a majority of respondents felt that computer simulations *"definitely have"* strengthened physicists' visualization capabilities both in respondents' own research area (51.6%) and in physics in general (52.5%).

Note in the descriptive statistics tables 4.2 and 4.3 on the next page, that responses concerning whether computer simulations have strengthened physicists' visualization capabilities in respondents own research area and in physics in general are similar on the positive end of the scale but differ on the negative end of the scale. For example, 3.1% of respondents said that computer simulations *"definitely have not/1"* strengthened physicists' visualization capabilities in their own research area compared to 0.9% in physics in general. The cumulative percentage for 7-point scale selections *1* & *2* & *3* is 17% for respondents' own research area, but only 7.2% for physics in general. The standard deviation is 1.87 for the former and 1.43 for the latter. [80]

As shown in section 4.5, an analysis of written explanations to Q4e suggests that the quantitative differences in Q4d may be because many of the physicists who responded to the questionnaire worked in areas where computer simulations were not used for the specific purpose of visualization. This may be because: (i) their work deals with abstract quantum mechanical concepts which are in-exact and therefore not easy to programme into a computer; (ii) their work is more concerned with calculating outcomes than visualizing physical processes; or (iii) as the findings in section 3.3 suggest many respondents have particularly good visuo-spatial I.Q. and/or prefer to use analogies, sketches or physical models instead of computer simulations.

Many of the respondents who made selections on the negative end of the 7-point scale for **Q4d(i)** (i.e. his own research area) but positive selections for Q4d(ii) (i.e. physics in general) did not explain their selections in **Q4e.** Among the respondents who did, was **Phys_194**, a 26 year-old, male, postdoctoral research fellow, involved in an "exploration of the interface between quantum physics and non-equilibrium driving." In response to

[80] As mentioned in chapter 2, my aim is not to show statistically significant correlations. I use the quantitative data in a qualitative way to uncover possible patterns which can be further investigated qualitatively.

Q4d(i) he was one of 19 respondents who selected ***2*** on the 7-point scale and for Q4d(ii) he was one of the 38 respondents who selected ***5*** on the 7-point scale. When asked in Q4e to explain his selections he added: "I think in essentially classical physics (fluid flow, for example) [computer simulations] have been very useful for visualisation. In quantum problems, it's not even clear what one should plot!"

Another factor that must be taken into account when analysing the computer simulation data is that many respondents were uncertain how to interpret the term 'computer simulation'. As mentioned in chapter 2, respondents' definitions of what computer simulations were, varied considerably. Interestingly, this often depended on the respondent's research background. For example, **Phys_ 19**, a 60 year old, male, Professor of Theoretical Physics indicated in his selection from the 7-point scale that he used computer simulations **"7/all the time"** in his research of "Atomic, molecular and optical and condensed-matter physics, occasionally nuclear. Notably: hevy-particle collision theory, Wannier above & below threshold phenomena and ferromagnetism, including fractals." He highlighted an experimentalist / theorist divide when he added:

> "I detest the word 'simulation': this is an experimentalist's derogatory description of modelling, algebra, analysis, numerical analysis, computational physics, computer programming, checking, testing etc etc. I effect theoretical and computational physics calculations as a large part of my research job (Personal Chair)"

Thus, the data must be viewed in light of this. (See also full dataset on the accompanying CD ROM and selected quotations in appendix 4, section A4.2).

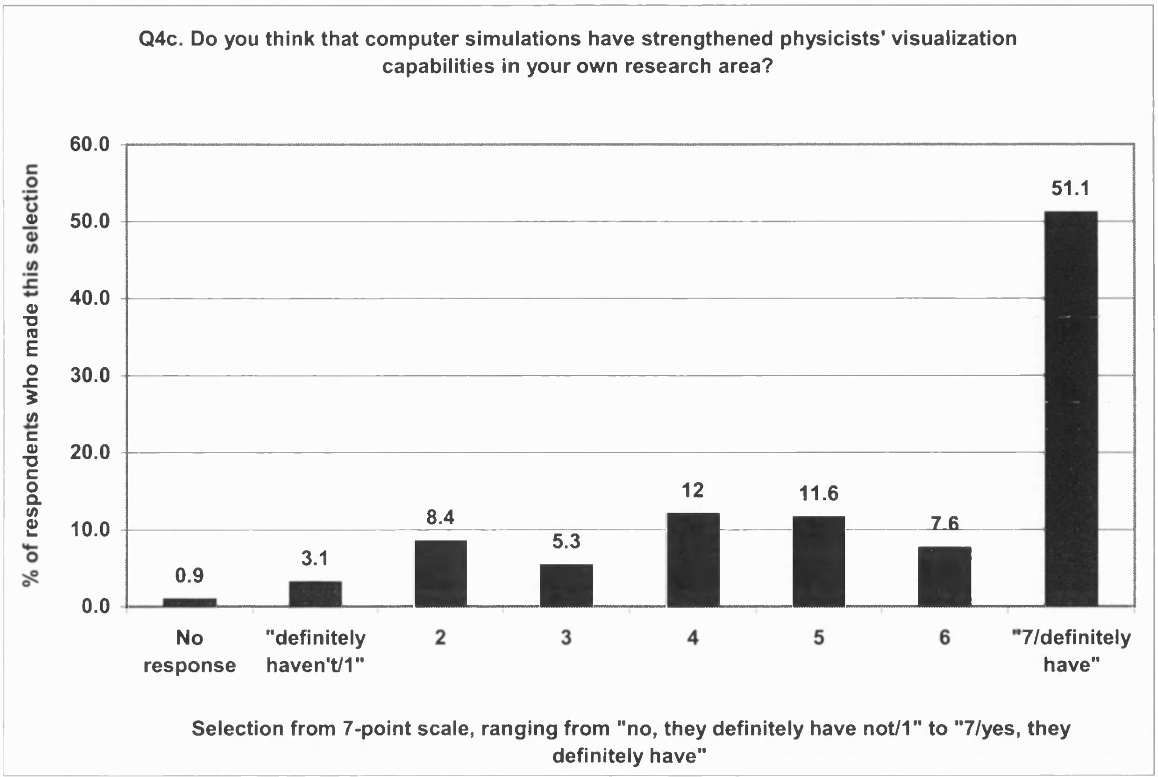

Figure 4.2: Chart showing % breakdown of questionnaire respondents' 7-point scale selections for Q4c.

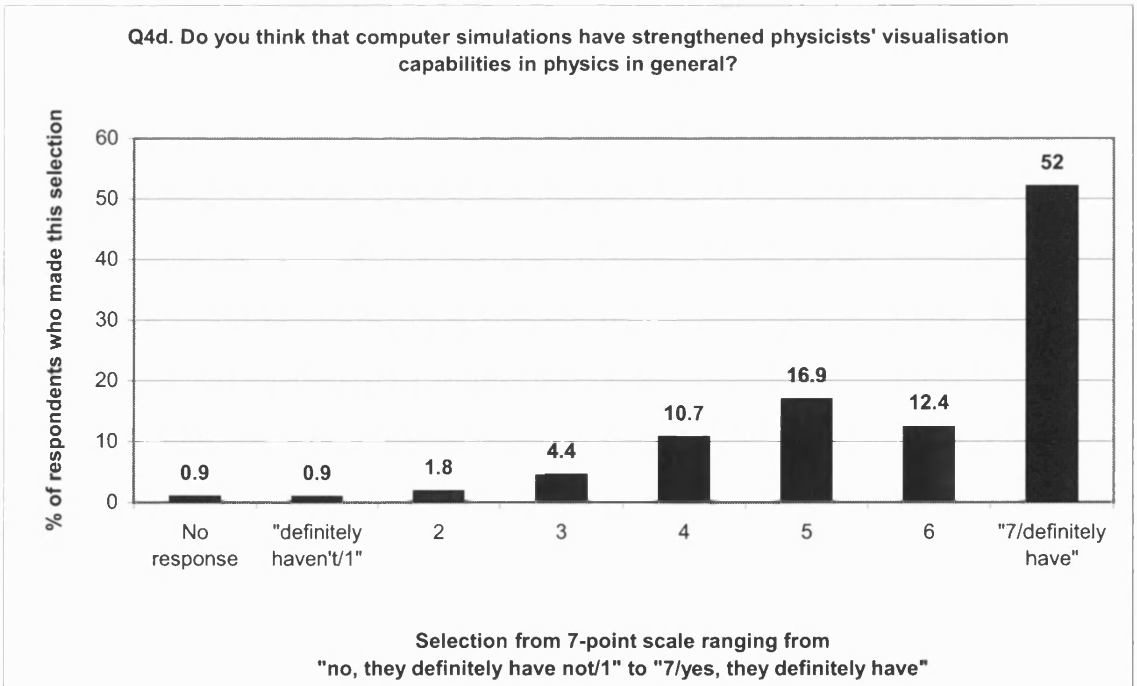

Figure 4.3: Chart showing % breakdown of questionnaire respondents' 7-point scale selections for Q4d (part 2).

Q4d. Do you think that computer simulations have strengthened physicists' visualization capabilities in your own research area?

7-point scale	Frequency	Percent	Valid Percent	Cumulative Percent	*Mode*	*Mean*	*Median*	*SD*
"definitely haven't/1"	7	**3.1**	3.1	3.1				
2	19	**8.4**	8.5	11.7				
3	12	**5.3**	5.4	**17.0**				
4	27	**12**	12.1	29.1				
5	26	**11.6**	11.7	40.8				
6	17	**7.6**	7.6	48.4				
"7/definitely have"	115	**51.1**	51.6	100				
Sub Total	223	**99.1**	100	100				
Missing Data	2	**0.9**						
Total	225	**100**	100	100	*7*	***5.5***	*7*	***1.87***

Table 4.2: Descriptive statistics for 7-point scale selections to Q4d of on-line questionnaire

Q4d. Do you think that computer simulations have strengthened physicists' visualization capabilities in physics in general?

7-point scale	Frequency	Percent	Valid Percent	Cumulative Percent	*Mode*	*Mean*	*Median*	*SD*
definitely haven't/1	2	**0.9**	0.9	0.9				
2	4	**1.8**	1.8	2.7				
3	10	**4.4**	4.5	**7.2**				
4	24	**10.7**	10.8	17.9				
5	38	**16.9**	17.0	35.0				
6	28	**12.4**	12.6	47.5				
7/definitely have	117	**52**	52.5	100				
Sub Total	223	**99.1**	100	100				
Missing Data	2	**0.9**						
Total	225	100	100	100	*7*	***5.89***	*7*	***1.43***

Table 4.3: Descriptive statistics for 7-point scale selections for Q4d (part 2) of on-line questionnaire

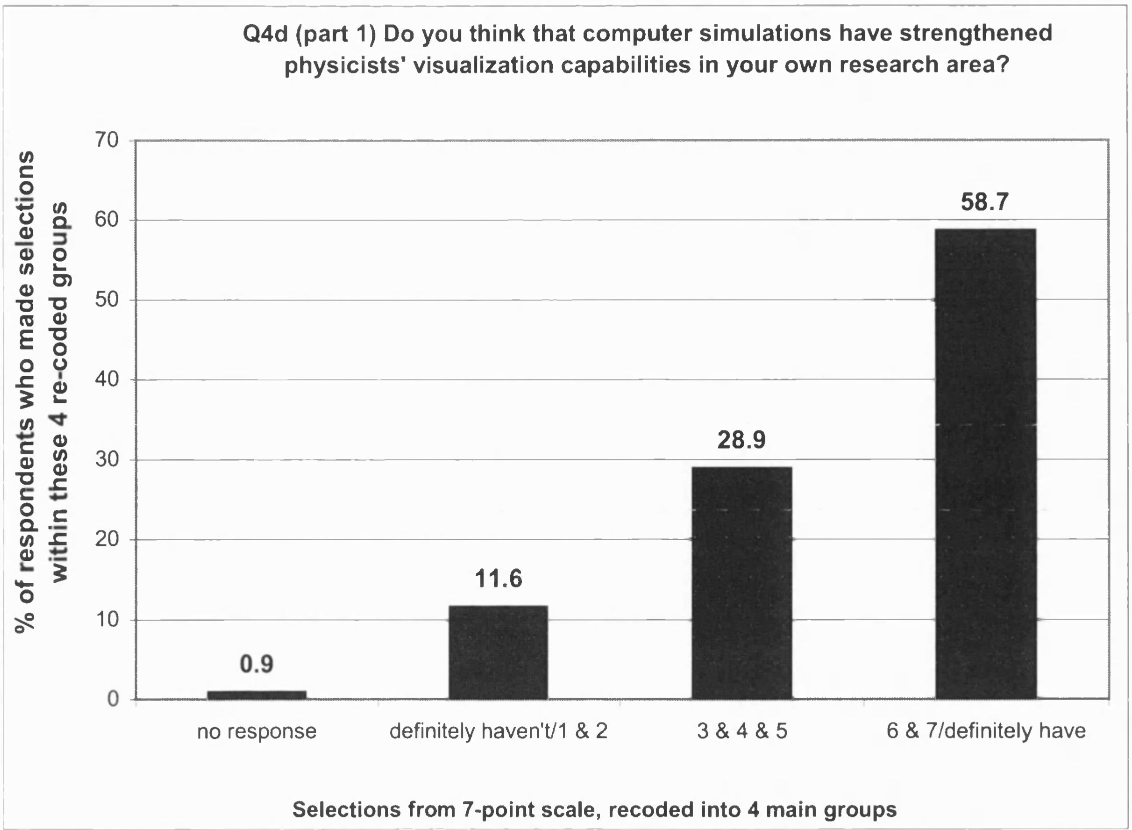

Figure 4.4: chart showing % breakdown of responses to Q4d (part 1) re-coded into 4 main groups.

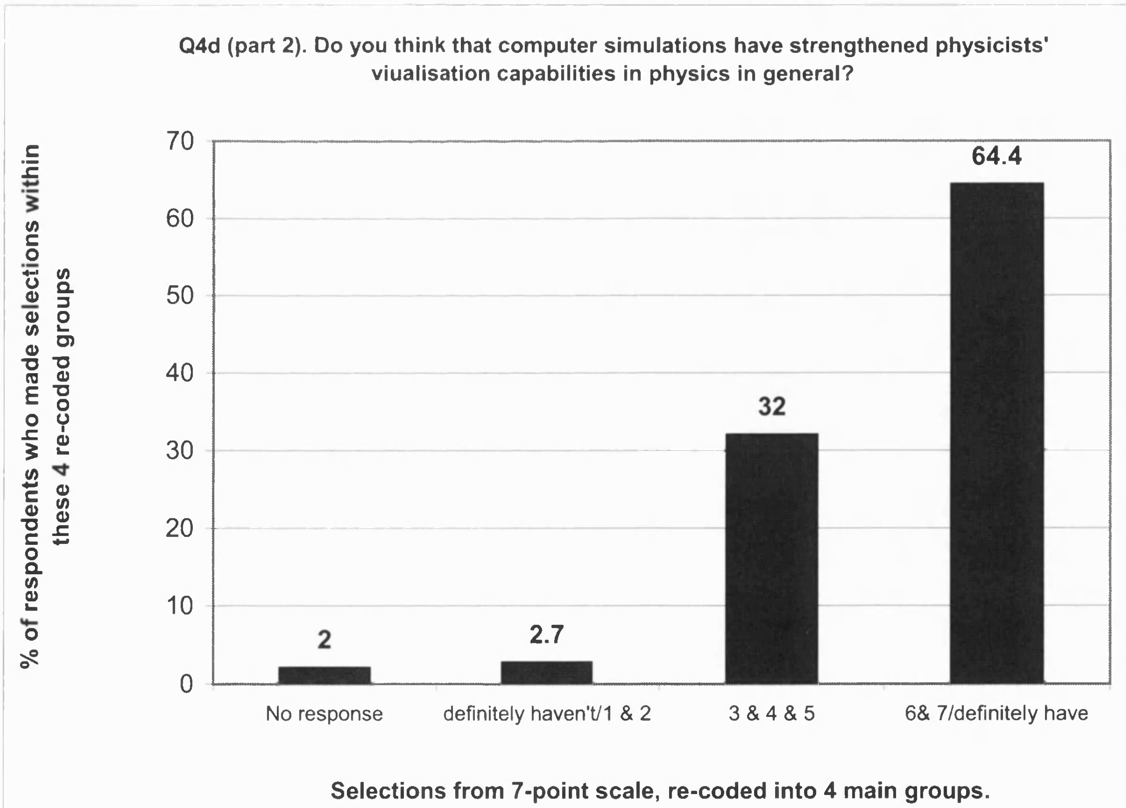

Figure 4.5: Chart showing % breakdown of responses to Q4d (part 2) re-coded into 4 main groups.

4.5 Respondents' verbal explanations of why computer simulations have or have not helped to strengthen physicists' visualization capabilities.

As mentioned in the previous section, respondents were asked in question **4e** of the on-line questionnaire: *"Can you please elaborate on your choice in Q4d above?"* Of the 7 respondents who believed that computer simulations *"definitely have not/1"* helped to strengthen physicists visualization capabilities in their own research area, only two respondents [81] appeared to hold negative or dismissive views regarding the worth of computer simulations as visualization tools. Most of the physicists whose responses were in the negative end of the scale explained that computer simulations were not used as visualization tools to a great extent in their own research areas because their work was either easy to visualise without the aid of computer simulations or, on the other hand, insufficiently advanced to allow for useful computer models to be written. **Phys_165**, a 36 year old, male, advanced research fellow was among the 7 physicists who said that computer simulations *"definitely have not/1"* helped strengthen physicists visualization capabilities in his own research (Particle Physics, Computational Physics, Hadron Physics, Lattice Gauge Theories, QCD) and among the 2 physicists who said this was also true for physics in general. However, he added in question 4e that a distinction must be made "between 'visualisation' where the advent of computers has not changed much and 'simulation'." He does believe that "simulating complicated physical systems is a genuinely new tool of scientific discovery." So although his quantitative responses were on the negative end of the scale regarding computer simulations strengthening physicists' visualisation capabilities, he recognises the value of simulations as discovery tools when used to simulate complex physical systems. As will be discussed in sections 4.5.3, 4.5.4 and 4.5.5, computer simulations provide a virtual laboratory with the type of control not possible in real physical situations. So although a small number of respondents believed that computer simulations have not helped strengthen physicists visualisation capabilities, the majority of respondents believed that computer simulations *"definitely have/7"* strengthened physicists' visualization capabilities both in their own research areas an in physics in general.[82]In their experience computer simulations can be used to produce visual representations of complex geometries, which would be extremely difficult to mentally visualize; follow the time evolution of complex systems; visualise solutions of equations etc. I will now discuss the main virtues of computer simulations drawing on the written comments of the 225 physicists who responded to the on-line questionnaire.

[81] Phys_200 & Phys_115 quoted in section 4.3
[82] (See appendix 4, section 4.1 for a list of additional quantitative and qualitative data on this issue)

4.5.1 Virtues of computer simulations: Visualization Tools:

Phys_63, a Professor of Astronomy, said that computer simulations definitely have strengthened physicists' visualisation capabilities in his own research area "studying the formation, evolution and structure of galaxies". He explained, "they certainly allow me to understand geometries that I would have trouble with on a piece of paper."

Phys_99, a lecturer in physics, said that computer simulations definitely have helped strengthen physicists' visualisation capabilities both in his own research area "Superconductivity in semiconductors; Quantum Electrodynamics and Vacuum Energy" and in physics in general. He listed some contexts in which computer simulations have proven useful: "Spatio-temporal chaos and the formation of patterns; molecular structures; velocity fields in hemodynamics; optical interference patterns; atomic orbitals. The list is simply phenomenal."

Phys_149, a senior research fellow, also believed that computer simulations definitely have helped strengthen physicists' visualisation capabilities both in his own research area "relativistic electron beams; free electron lasers; collective radiation-matter interactions" and in physics in general. In his experience, "Visualisation can make abstract mathematical models come alive. You perceive the mathematical solution in a way that taps into the very fundamental sense of sight and therefore perhaps utilise a large sub-conscious processing power that is not available from the purely abstract."

Phys_95, a PhD student, indicated [83] that computer simulations have strengthened physicists visualisation capabilities both in his own research area "building / testing meteorology sensors for Mars landers; Experimental physics; Fluid dynamics; Thermal analysis" and in physics in general. He said that in his own area, most fluid dynamics calculations are now done on computers, with "only a few isolated experimental data points obtained in wind tunnels for confirmation." The computer output he works with "can be visualised with many colors, axes etc in a very instructive way." He remarked that his own work "generally deals with phenomena on a human scale - as such it is fairly easy to visualise much of what is going on." He contrasted this with other areas of physics where researchers deal with "either the very large or the very small" and "behaviour at these scales is less intuitive and can be more difficult to visualise (especially quantum processes!)." In his experience, some researchers in these fields "seem to understand processes entirely through mathematics, without recourse to visualisation (which they feel can be dangerously misleading)." For researchers like himself, who normally deal with classical and semi-classical physics, and phenomena on human scales, "computer

[83] (He selected _6_ on the 7-point scale for both parts of the question)

visualisations have been tremendously useful in these fields [e.g. when dealing with quantum processes] because they let the rest of us know what on earth they're talking about!" I believed that this was a particularly important finding and (as discussed in section 3.6) I raised the issue with several theoretical physicists during my follow-up e-mail exchanges.

Also, as mentioned in chapter 3, research by cognitive scientists suggests that: "Prior exposure [to diagrams and other kinds of images] can lead to perceptual fluency in recognition and classification." (Chandrasekran & Narayanan, 1992, p.30). So, might exposure to complex geometries and evolving systems strengthen one's ability to generate visualizations unaided by a computer? The comments of **Phys_158** & **Phys_179** suggest so. **Phys_158**, a PhD student, indicated that computer simulations have to a certain extent (i.e. 3/7) strengthened physicists' visualization capabilities in his own research area, "Quantum cryptography, quantum key distribution" but have done so to a much greater extent (i.e. 6/7) in physics in general. He said: "personally I think that there is a limit to what a human can visualise if we have not seen something like it before. By using a computer we can increase our own data bank of unusual images to help increase our powers of visualisation." Similarly, **Phys_179**, also a PhD student, indicated that computer simulations have to a certain extent (i.e.4/7) strengthened physicists' visualization capabilities in his own research area, "magnetic interactions within 1- and 2-dimensional arrays of nanomagnets, constructed from magnetic-cored ferritin proteins and superlattice nanowire arrays" and in physics in general (also 4/7). Elaborating in Q4e, **Phys_179** wavered between the virtues and vices of computer simulations as visualisation tools remarking: "I'm not sure if the programs strengthen our visualisation capabilities (the programs themselves were initially visualised to be written) or if they stop us from having to, making life easier but not using our minds any more so. Maybe they do help though, providing a 'platform' to use in future to visualise, away from the screen."

4.5.2 Virtues of Computer Simulations: Exploration of Complex Systems by Controlling and Varying Parameters.

Aside from the virtues of visualisation, my data revealed that computer simulations are also extremely useful for exploring the response of systems by controlling and varying different parameters. For example, **Phys_111**, a research student investigating "Epitaxial Systems, Non Equilibrium, Probabilistic Description" remarked that it "depends on what you mean by visualisation." He said, "if you mean complete visualisation then it probably does not help, but it certainly allows us to do 'ideal' experiments under controlled circumstances." **Phys_205**, a postdoctoral researcher, is involved in, "Turbulence research in astrophysics (fluid mechanics, numerical hydrodynamics, turbulence modelling); application in stellar astrophysics." He said that computer simulations definitely have strengthened physicists' visualisation capabilities both in his own research area and in physics in general. He noted that, "studying physical systems in several (spatial) dimensions has always been an enormous challenge to physicists." Computer simulations "provide a laboratory with a type of control not possible in real physical systems."

Phys_74, a research fellow, noted that: "It is impossible to probe certain functions systematically without computers (this is not necessarily 'simulation' in the sense used by some physicists, but is definitely visualisation)." He said that much is his research "in fundamental physics (eg classical crystal optics, statistical geometry of stochastic functions) would have been impossible without computer visualisation techniques." Similarly, **Phys_43**, a lecturer, said that, in his research into laser plasma interaction particle acceleration, he deals with "extremely complex, multi-body systems, for which analytical solutions or treatment are of limited use." He said that fortunately, "computational codes (thanks to the ever increasing computer performances) can deal with demanding numerical calculations and provide visual outputs. In particular, in codes it is possible to switch on and off particular phenomena or effects and see their impact on the final results (which is not possible in experiments in most cases)."

This has parallels with the neighbouring field of engineering where Bissell & Dillion (2000, p.10) tell us that well-designed computer-based tools can contribute to a clearer understanding of systems behaviour. They can "enhance expertise by allowing the engineer to use the processing power of the computer to explore easily and quickly the predicted effect on system behaviour of different design strategies." One advantage is that "this exploration is carried out directly in the language of the engineer, rather than in that of the mathematician." The "language of the engineer" is usually a more concrete language than that of the mathematician, as we shall see in chapters 7 & 8 in my case-study of Dr. Lawson, an engineer-physicist. In a similar vein, many questionnaire respondents remarked that computer simulations allow them to tweak parameters and probe functions systematically, allowing for greater understanding of the system.

4.5.3 Virtues of Computer Simulations: Simulating Physically Impossible Experiments.

Many respondents pointed out that computer simulations provide a laboratory with a type of control not possible in real physical systems. This virtual laboratory allows physicists to perform experiments that are too expensive, technically difficult or physically impossible to perform. Visualization is central in some of these instances and merely a by-product in others. For example, **Phys_4** is a senior research scientist whose research interests include: “Laser material interaction with particular reference to short pulsed lasers such as femtosecond lasers, experimental studies and numerical modelling.” This is a “broad inter-disciplinary area spanning electro-optics, plasma physics, materials science and applied mechanics.” He said he can “get at information in simulations that is physically impossible to obtain with experimentation, e.g. the temperature in the bulk of a target being irradiated with a laser beam... A simulation solving the fourier heat conduction equation in 3D will however yield most of the relevant information.” Similarly, **Phys_25**, a 40 year old Senior Lecturer whose research interests include “x-ray scattering from dense plasmas as a way of finding out their properties e.g. electron-ion equilibration times” said that: “Many interesting behaviours are only revealed using the power of simulation. In my own field we realised that some of our plasmas emitted x-rays longer when hit by a more intense laser, not because of the reduction in recombination rate which intuition told us was the answer but because of a sustained collisional ionisation rate as revealed by simulation. This latter is a rather technical example.” **Phys_ 95**, a PhD student who builds and tests metrology sensors for Mars landers (whom we met in section 4.5.1) replied saying: “Before we build a piece of hardware, we always make technical drawings of it, often with 3D visualization.” He explained that: “for every physical experiment performed, I tend to perform 3 computer experiments.” He creates “thermal models of systems” and said he “can simulate many more configurations using a computer than in real life.” In the experiences of **Phys_220,** a Higher Scientific Officer involved in “radiation protection - occupational exposure to radon,” computer simulations “help with visualisation, especially when the objects are outside our normal, everyday view, e.g. nuclear interactions.”

4.5.4 Virtues of Computer Simulations: Visualization is a useful by-product.

Some respondents were keen to emphasise that visualization is **not** the most significant factor in their decision to employ computer simulations in research. They said computer simulations are used in numerical modelling **not** as a visualization tool, but simply to calculate outcomes. As **Phys_ 139** (a lecturer involved in biophysics) put it, “Simulations have increased understanding. Visualization is a by-product.” Similarly, **Phys_143,** (a PhD student) remarked that, “Computer simulations allow systems to be reduced to a simpler form, hence identifying characteristic behaviour. They allow predictions to be made. I wouldn’t imagine that 'visualisation' is the most important aspect of computer simulations." Visualisation of simulated data makes it easier to understand what the model is doing and therefore to evaluate it. It is not necessarily a direct source of physical insight, but is often used in the same way as visualisation of empirical data from real experiments. The physical insights are partly designed into the simulation model and partly extended by the ability to play with it. This is in contrast with the role of visualisation in modelling, where it may be a direct expression of physical, biological or other insights. Thus, for example, in **Phys_75's** experiences, simulations are essential in understanding results from particle physics, since the phenomena are so far outside the human scale. However, "in physics in general, simulation is often only used as a tool to 'crank the handle' on a model, rather than to obtain real physical insight." Similarly, **Phys_50**, (a professor of experimental physics) remarked that, "Things like molecular dynamics simulations are not there to strengthen visualisation but to calculate outcomes."

Interestingly, many respondents remarked that it was in fact very difficult to distinguish between the use of computer simulations to solve problems and the use of computer simulations for the purpose of visualization. For many, the two were "inextricably linked." For instance, **Phys_185**, a research fellow, involved in "quantum computing, quantum many body physics, phase transitions, physics of information," said she has "colleagues who have explicitly put together visualisation systems to help their research. On the other hand, I don't really distinguish between computer simulations to solve problems and computer simulations to visualise processes..." Likewise, **Phys_ 160**, a Reader in Theoretical Physics, believes that computer simulations "have had an enormous impact on almost every aspect of physics. In many cases, they provide tools which actually solve problems that could not be tackled in any other way." However, he emphasises that "it is probably impossible to distinguish meaningfully between (a) computations which produce the desired answers, conveniently presented in a visual format, and (b) the use of computer graphics to aid visualization. I think the two things are inextricably linked."

Thus, the questionnaire data presented in section 4.5 illustrates that a majority of respondents believe that computer simulations have strengthened physicists' visualization capabilities in their own research area and in physics in general. Their virtues include visualisation of complex geometries, exploring complex systems by controlling and varying parameters, providing physicists with a virtual laboratory in which to simulate physically impossible experiments. Visualisation is almost always a useful by-product, but not necessarily always the main goal. Computer simulations may also be used for the sole purpose of numerical modelling or number crunching. Having discussed the virtues I will now address the vices.

4.6 The Possible Disadvantages of Using Computer Simulations:

Question 4f of the on-line questionnaire posed the following question:

"What, in your opinion, are the possible disadvantages of using computer simulation"?

4.6.1 No Disadvantages:

Seven respondents (**Phys_16, Phys_80, Phys_129, Phys_153, Phys_189, Phys_196, Phys_110**) could see no disadvantages. As Phys_80 said: "None - they are essential in my field [star formation, astronomy, biological systems]." I believe it is relevant that most of these physicists work in the related fields of space science, galaxy formation and cosmology. As it is often impossible to physically carry out experiments in these fields, computer simulations are the nearest things one can get to 'experimental data'. A post-doctoral researcher in cosmology, **Phys_110**, remarks that: "Many simulations in cosmology (galaxy formation simulations, Lyman Alpha forest simulations) are unphysical because of the lack of understanding of physics and because of the lack of resolution but both improve and these are early days yet." She notes that "Boltzmann codes to simulate CMB [Cosmic Microwave Background] data are the exception, being based on plasma physics 50 years old and carried out on computers easily, big and fast enough to make the results quite accurate." While most respondents extolled the virtues of computer simulations on account of the knowledge to be gained into the workings of the modelled system, there was overwhelming agreement and widespread concern that computer simulations **could** lead physicists astray **if** they were misused. I have grouped these concerns thematically in the following sections.

4.6.2 They May Encourage Laziness and Weaken Innate Visualization Abilities:

Five physicists,[84] representing a range of ages (in their 20s, 30s, 40s and 50s respectively) mentioned that computer simulations might make physicists "lazy". **Phys_ 177**, a PhD student, working on quantum communication and information theory, said simply that a possible disadvantage was that computer simulations, "can make us lazy." **Phys_116**, a lecturer, involved in solid state physics, suggested a possible disadvantage was a, "loss of imagination, increase of laziness." **Phys_41**, a lecturer in astrophysics said that they: "may make researchers 'lazy' in the sense of making them less likely to try to find analytical solutions to a problem, although such analytical solutions can often offer insight." **Phys_78**, a Reader in Physics, said a possible disadvantage is that it, "Encourages laziness, discourages personal interaction ..." **Phys_215** said, "they can sometimes have a harmful

[84] Phys_177, Phys_116, Phys, 41, Phys, 78, Phys, 215

effect - people get carried away with generating 'pretty pictures' and they can become lazy. Rather than seeking to understand, derive and simplify formulae, they just stick them into a program." One could ask if **Phys_215's** reference to 'pretty pictures' is related to his initial training as an engineer. [85] In her study of the visual culture of engineers, Henderson, (1995) says that renderings in perspective are used to generate financial and organisational support for design and commercial promotion. These renderings are drawn by illustrators, not engineers, "who have been known to scornfully refer to them as 'pretty pictures'." (Henderson, 1995, p.203).

Other respondents were also slightly concerned that using computer simulations as visualization tools may have a negative affect on some individuals: acting as a mental crutch it may weaken their innate visualization abilities. However, they were not suggesting that physicists should avoid using computer simulations as visualization tools because, as they themselves have found, computer simulations are powerful visualization tools in numerous contexts. They were instead advocating a cautious use of computer simulations, informed by studies such as this one, which aims to find out what works and what doesn't work, according to the practitioners themselves. For instance, **Phys_166** said, "one may become less able to construe mentally certain geometrical functions or shapes if one finds easier to resort to a computer simulation (but presumably, this may make more time available for other activities)." **Phys_ 127** also wavered between pros and cons. For example, he said one disadvantage was the "loss of mental ability to be creative in visualisation." However he qualified his remark by adding, "that's just a prejudice, though -- personally I find that familiarity with graphical representations help me to be more mentally inventive." He concluded with a disadvantage saying, "there's a danger of thinking that the program's representation is the only way, though..." **Phys_155** also alternated between the pros and cons of using computer simulations. On the positive side she said, "I think getting the computer to do the visualisation for us can be detrimental for our own imagination of the graph to be obtained before it is actually generated." However, she added, "on the other hand, generating one graph can lead to speculations on variants of that graph and thus hone our imagination."

[85] He holds a BEng in Electrical/Electronic Engineering as well as an MSc in Optics (physics), and was writing up his PhD on Laser Optics (physics) when he replied.

4.6.3 The Immediacy of Graphical Images Can Be Powerful But Misleading

Three respondents from the fields of astronomy and astrophysics remarked that an image is a powerful thing and its immediacy can be misleading. **Phys_22** (a PDRA in astronomy) said the disadvantage was: "mainly in people forgetting to bear in mind that these are only simulations, not definitely showing what is going on (an image is a powerful thing) … " **Phys_21** (a lecturer in astrophysics), said: "It is very easy to be misled by results from computer simulations which appear to be physically reasonable, but in fact are a result of some bug/weakness in the simulation itself. One needs to maintain a very critical approach to simulation results, in spite of the bright colours and nice pictures, and many people do not." **Phys_205**, (a PDRA), said the danger was: "To believe too much in the nice pictures usually displayed at the end of such work: they are also usually based on approximations and their impact is more readily ignored if 'convincing' evidence is given in graphical form." It makes sense that these three respondents come from the fields of astronomy and astrophysics. The scientific realism of images is particularly relevant for researchers in these fields. Many astro-images have become 'iconic', adorning computer desktops and regarded by many as works of art. An image of the Eagle Nebula (created by Jeff Hester and Paul Scowen of Arizona State University / NASA) was voted second most influential astrophoto of the 20th century by the readers of Sky and Telescope. [86] It has appeared on many magazine covers and posters and was among four images chosen for a special set of US stamps to commemorate the 10th anniversary of the Hubble Space Telescope. The photograph is a false-colour image. It is shown in fig. 4.6 below.

Figure 4.6: The Eagle Nebula. Credit J. Hester & P. Scowen, Arizona State University / NASA.

[86] The number one spot went to the so-called 'Earthrise' photo taken during the Apollo 8 lunar mission.

In a special issue on "iconic images" in **Physics World** magazine Muldoon & Rodgers[87] write that:

> "Although the false colours are undoubtedly eye-catching, Scowen stresses that they are chosen for scientific reasons rather than principles of realism or aesthetics. For instance, the hydrogen is coloured green in the image, even though it is really red, because sulphur is also red and astronomers need some way of telling them apart." (Muldoon & Rodgers, 2002, p.35).

Scowen said that he always tries "to highlight the scientific value behind the images as well, so that the public sees more than the simple 'gee whiz' factor." (ibid.) The issue of scientific realism surfaces again, in section 4.12 when Prof. Berry discusses his deliberate use of artificial colours in order to dissuade people from taking his abstract mathematical representations to be literal pictures of physical phenomena that could be seen in the natural world. Berry's images have won awards in 'science as art' competitions. However, like Scowen, Berry is keen to emphasise the scientific value of his computer-generated images so that the public see more than the simple gee whiz factor.

4.6.4 It is hard to know the extent to which they accurately reflect reality: Experimental checks are necessary

A large number of written/verbal responses to Q4f related to the view that computer simulations could be particularly dangerous if they were not used in conjunction with other physical method, i.e. if, in an extreme scenario, physicists were to become disembodied experimenters working solely in an imaginary computer micro-world. Of the 225 physicists who responded, 18 respondents specifically referred to the reality status of computer simulations, when asked about the possible disadvantages of employing computer simulations in research in question 4f of the on-line questionnaire. (A full set of 18 responses can be found in appendix 4, section A4.2). Boon (2006) identifies a distinction between scientific & technological practices, arguing that:

> "...scientific and technological practices employ different *quality criteria* or *epistemological norms*. Depending on ones position in the realism debate, norms in science are truth, universality, theoretical consistency, coherence, simplicity, empirical adequacy, and approval by the scientific community. Quality in technology means the practical success of a technical solution and approval by the engineering and industrial practice; other epistemological norms in technology are applicability, reliability, effectiveness and efficiency."

[87] I worked with Physics World editor Peter Rodgers during my MSc in Science Communication.

The respondents of my on-line questionnaire came primarily from basic science, although there were some researchers involved in applied science. Some respondents were theoreticians involved in highly abstract areas of quantum physics; some were experimentalists involved in designing, testing and building equipment; some were computational physicists bridging the divide between theory and experiment. I have not been able to identify a clear-cut relationship between these 18 respondents' research areas and their views on computer simulations. However, I do believe there may be an age related skew: older respondents tended to mention the reality status of computer simulations to a greater extent than younger respondents. For example, of these 18 physicists, 2 were in their 20s, 4 were in their 30s, 4 were in their 40s, 3 were in their 50s, 3 were in their 60s, 2 did not specify their ages, but said things like "old". If we express this as a percentage of the total number of respondents in each age bracket, there does appear to be an age related skew.

Re-coded Age Ranges of Respondents	Total no. of respondents in this age category	No. of respondents in this age bracket who used the words 'real' or 'reality' when discussing the disadvantages of computer simulations	As a % of total no. of respondents in this age bracket
19-29	92	2	**2.2**
30-39	57	4	**7.0**
40-49	39	4	**10.0**
50-59	26	3	**11.5**
60-67	8	3	**37.5**
Sub-Total	222	16	7.1
Indeterminate	3	2	66.7
Total	225	18	8

Table 4.4: Shows that older respondents tended to mention the reality status of computer simulations to a greater extent than younger respondents.

Phys_162, (a 55 year-old professor of solar-planetary physics) said: "It is hard to know to what extent they accurately reflect reality, and there is the possibility of being fooled by them." **Phys_121,** (a 59 year old, male professor) said that "Care [is] needed in setting up the simulation to make it represent reality. Experimental checks are needed" **Phys_136,** a 63 year-old Professor of physics said: "It's not 'real' physics. You must always be careful to make it as physically realistic as possible." **Phys_ 217** (a 66 year old, reader) said that the main disadvantage is: "to mistake the model for the 'truth'. This has always been a danger of any model (ie any approximation), including Newton's mechanics and Einstein's special relativity."

Although 8% of respondents seemed to take a realist stance, when they were prompted to reflect on the disadvantages of computer simulations, the majority of respondents did not seem to take a strong realist stance. On the whole, most physicists seemed to be concerned with speed, efficiency, usability, empirical reliability and empirical adequacy. They would probably share Morrison's (1998) instrumentalist view which holds that in scientific practice, models are not judged on how well they map onto reality; they are judged on their adequacy to predict and calculate, to design equipment and measure outcomes. For example, Morrison contends that:

> "Theory plays a role in the construction of models in physical optics but the models in each domain stand on their own as a source of information for practical problem solving. There is no worry that the models do not map onto an accurate realistic account of the nature of light, on the contrary, it is their idealized structure that makes them useful as instruments in the design of lenses and for the calculation of different effects produced in different experimental contexts." (Morrison, 1998, p.73)

The number of assumptions made in building the model and the empirical reliability of the results are vitally important factors, but are constantly weighed up with the requirements of the user. As Gooding, (2005, p.176) notes, when dealing with models, "there is always a tension between complexity and realism on the one hand and solvability on the other." Koponen (a practicing physicist) argues convincingly that:

> "Physics does not require strong realist interpretations; more important than truth are the *empirical reliability* of knowledge. The empirical reliability of models (or theories) requires only that they produce empirically successful predictions and that the reliability is established in a methodologically accepted way. These are the minimal (and often only generally agreed) criteria for knowledge in physics. Moreover, whether or not the empirical reliability has been fulfilled can be evaluated and assessed, contrary to the claims of 'truth' and 'reality' which are beyond such scrutiny." (2006, draft, p.15)

In fact, 8 respondents remarked specifically on the importance of establishing the empirical reliability of models in a methodologically accepted way, i.e. via <u>experimental checks</u>. (The full list of 8 responses is contained in appendix 4, section A4.3). For instance, **Phys_121**, a 59 year old, Professor of Physics said that: "Care needed in setting up the simulation to make it represent reality. Experimental checks are needed." Similarly, **Phys_58**, a 31 year old, lecturer asked: "do you believe the model? - it has to be tested against experiment." Thus, my findings support Cartwright's (1999, p. 9) stance that: "...

we tailor our systems as much as possible to fit our theories, which is what we do when we want to get the best predictions possible." Interestingly, **Phys_ 105**, a 31 year old, PDRA whose research interests include, "biomineralization, magnetism, material science" underscored the importance of tailoring a computer model with exact experimental results, but found this difficult to do in practice because, in his view, many experimentalists believe computer simulations are superfluous. In **Phys_105's** words:

> "It is highly dependant on experimental results and also on how the experiment was conducted. A good calculation needs to be coordinated with experimentalists but unfortunately most experimentalists don't understand the computation methods well enough probably because they are convinced they can do without computations."

I share Koponen's view that the empirical adequacy of models is established by a three-phase process of match-making:

> "...first, between experimental data and empirically reliable models (empirical substructures); second, between empirically reliable models and theory (or theoretical models); and third, between empirically reliable models and phenomena themselves."
> (2006, draft, p.23)

However, it seems that even when models are established as empirically adequate, some physicists remain sceptical. As **Phys_137,** (a 40 year old, Reader in Physics, who often uses computer simulations of lattice field theory) quipped:

> "...there is a prejudice, which I share on Tuesdays and Thursdays, that numbers from a computer, however well they agree with experiment, do not communicate any fundamental understanding."

These findings are extremely interesting and should, in my view, be pursued further in more in-depth, future research.

4.7 Can computer simulations provide physicists with insight?

The importance of acquiring (physical) insight appeared on numerous occasions in the on-line questionnaire's section concerning the possible disadvantages of using computer simulation in Q4f. **Phys_119** and **Phys_107** quoted Richard Hamming, who once said that: "The purpose of computing is insight, not numbers." Of course the same could be said of experiment, numerical modelling, etc. In general, most references to insight suggested that computer simulations could not offer real insights on their own, but could offer limited insight if physicists improved their understanding of their model by using analytical methods and therefore did not use them as black boxes. For example, **Phys_183** said, that, "physical insight can be lost when simulation is a 'black box'. simulation should only be used alongside mathematical analysis to get the whole picture." **Phys_119,** also referred to a black box type scenario saying: "I suppose it is also a bit like what is wrong with school-kids using calculators. If you depend on the box, you sometimes fail to look after your 'physical insight' -- your understanding and internal predictive ability." In her experiences, "simulation lets you see what YOUR MODEL predicts. It doesn't prove you have the right model, although very good agreement with actual data would perhaps persuade you that your model had potential." **Phys_89,** on the other hand, mentioned theoretical insight, saying that computer simulations: "cannot by themselves provide theoretical insight, nor replace real-world experiments." It is not completely clear what these physicists mean when they talk about 'theoretical insight' or 'physical insight'. For some physicists 'insight' seems to have visual and pictorial connotations, e.g. getting the "whole picture". On the other hand, **Phys_119** defines "insight" as "your understanding and internal predictive ability," which is somewhat similar to the Gestalt psychologist Köhler's interpretation of insight as an "understandable relationship". (Köhler, 1947, p.326). In chapter 8, I will explore the meaning of the term insight in more depth, when analysing the scientific papers of J.D. Lawson.

In order to give a more **visual** account of the types of simulations used by researchers in his field, **Phys_54** provided a link to the *Cambridge Cosmology* web-page, hosted by the Department of *Applied Mathematics and Theoretical Physics* at the University of Cambridge. On this website, the Cambridge team pose the question, "why are simulations useful" and answer it by saying that: "although the movies are in some sense a nice by-product of the simulation, they can provide extremely useful insights into the detailed dynamics of the strings." They explain that because e.g. cosmic strings are extremely complex non-linear objects, "the only rigorous way to study their evolution and cosmological consequences is therefore to simulate it on the computer." Figure 4.7 below, taken from their section on "Comic Strings and Other Defects" simulates the dramatic effect of radiation for two interlocking loops. The Cambridge team add that, "this configuration is unlikely to happen in a cosmological setting, but it is nevertheless quite enlightening. Notice the succession of complicated dynamic processes before the loop finally disappears!" This fits with the stance put forward by Morgan and Morrison (1999). They note that:

> "A simulation, by definition, involves a similarity relation yet, as in the case of a model's predictions mapping on to world, we may be able to simulate the behaviour of phenomena without necessarily knowing that the simulated behaviour was produced in the same way as it occurred in nature." (Morgan & Morrison, 1999, p.29)

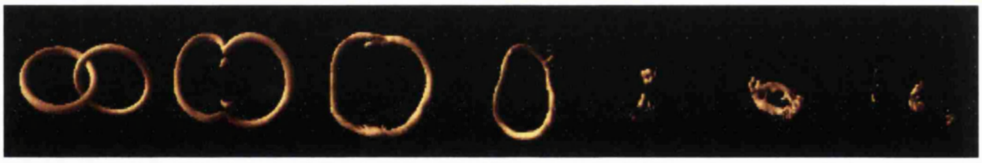

Figure 4.7: Snapshots from a simulation showing the intersection, unification and decay of two interlocked loops. The accompanying caption reads: "Note that when the united loop finally collapses to a point and annihilates, there is sufficient energy available to create a `transient' new loop, just as in the long-string intercommuting case above (R. Battye & E. P. Shellard)" Source URL: http://www.damtp.cam.ac.uk/user/gr/public/cs_interact.html

So here again, we have evidence that computer simulations can offer "insights" and be "quite enlightening" even when a particular configuration is unlikely to happen in a cosmological setting. The Cambridge team are keen to point out that in order to obtain a more **accurate** and more **detailed** description of the evolution of cosmic strings, it is necessary to use high-resolution numerical simulations. For example, figure 4.8 below is a snapshot of a simulation of an initial string box containing "a configuration of strings such as one would expect to find after a phase transition in the early universe." The computer model then evolves this initial box, by using the laws of motion of the strings to determine how it should look at a future time. This process is repeated for a large number of timesteps then converted into frames and combined to form movies.

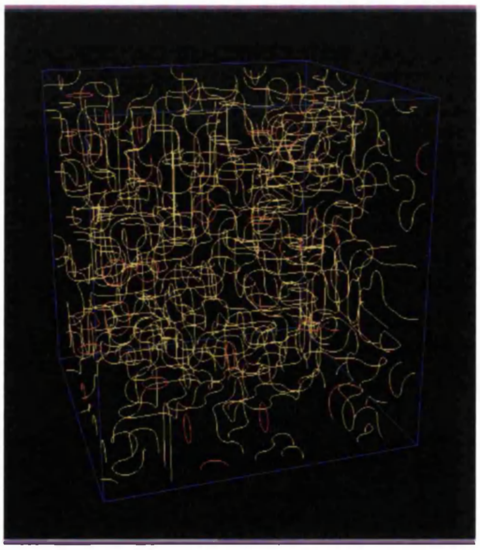

Figure 4.8: ***"A snapshot of a typical initial string box. Notice that the displayed box is only a fraction of the total simulation box. (C. Martins & E. P. Shellard) "*** Taken from Cambridge Cosmology, a website created by the Department of Applied Mathematics and Theoretical Physics at the University of Cambridge.
Source URL (as of April 2006): http://www.damtp.cam.ac.uk/user/gr/public/cs_evol.html#model

These simulations are very difficult to perform, and require extremely long CPU times. Thus, the Cambridge team remark that, "one of the aims in performing numerical simulations of the evolution of cosmic string networks is to subsequently use the resulting information as an input to build (relatively) simpler **analytic models** that reproduce (in an averaged sense) the crucial properties of these objects."

Thus, the comments and examples presented here suggest that computer simulations do provide many physicists with useful insights even when their configurations may be unlikely in a cosmological setting. The simulations are used to build simpler analytic models that are useful in making quantitative predictions about the implications of e.g. cosmic strings. This provides additional supporting evidence for Koponen's contention that "physics does not require strong realist interpretations; more important than truth are the *empirical reliability* of knowledge." (2006, draft, p.15). I will continue with my exploration of issues surrounding visualisation, analogy and computer simulations in section 4.8 by presenting material from my semi-structured interview with Professor Sir Michael Berry. In particular, I will present data on Prof. Berry's experience of using computer simulations to hone his already well-developed geometrical intuition.

4.8 Can Computer Simulations Help Physicists Develop a Geometrical Intuition?

As mentioned in chapter 2, I pursued several interesting findings from the on-line questionnaire via follow-up e-mail exchanges with 13 questionnaire respondents, a case study of Dr. Lawson's work, and an interview with Prof. Berry. During my interview with Prof. Berry I asked if visually representing and expressing different phenomena actually provides him with a better understanding of it himself. He said it did, adding:

> "… representing phase using colour. Now when you do that you get… very immediate representations. In my case it's waves… we discovered many things from using these pictures, they were visually obvious – and when we saw them, we said 'well we hadn't realised the equations had that in them', then we went and understood it mathematically. But this is all within the world of theory. It's not like looking at a picture of something that you haven't seen before, a picture that comes from nature."

Berry's distinction between pictures confined to the world of theory and pictures that come from nature could be compared to Miller's (2000, p.310) distinction between "visualizability (visual images generated from scientific theories)" and "visualization (visual images abstracted from phenomena we have witnessed in the world of perceptions" discussed in sections 1.1 &1.4). Prof. Berry is very keen to emphasise that his pictures are mathematical abstractions: "entirely in the world of theory" as he explains:

> "You've got mathematics which is expressed compactly as equations, but the content is...very densely coded. Elegant, beautiful, but densely coded. Our formulae are often wiser than we are. And indeed by looking at the pictures and observing that certain features are separate when we thought they would be co-incident with each other we get a new understanding."

Prof. Berry says, "it is part of the process of understanding and making discoveries. It has been with us to look at pictures and see things in them which we hadn't expected. So it's not just presenting something I know already. It's part of the process." Again, to quote Miller (2000, p.324) on this issue: "The partially interpreted symbols in scientific theories can then attain meaning of a descriptive and depictive sort. The accompanying visual imagery is effective in problem solving and can have truth value."

I asked Prof. Berry: "So they're generative? You come up with new ideas?" He responded: "Exactly. I wouldn't say it's a HUGE part of the process. I mean visualizing is. But [computer simulations are] a part of the process." I probed deeper, asking: "so do they help you to develop a **geometrical intuition** as to what's going on with the equations?" Berry replied:

> "Exactly. Exactly. Now people are very different in this. There are physicists that I enormously respect that have made huge contributions that don't think visually at all. I find that very strange because I do [think visually]. Actually I say I find it strange, it took a while for me to learn it. And that might be an unexpected thing. Because you think of visualising as something even children might do. I mean it might be, but you can lose it ... I used to think completely algebraically and linearly - - I still do, I mean that's part of the work clearly - - but that was all I did when I first came to Bristol in my 20s. But I learned that there was a culture here of pictures - - there was a visual culture - - long before computers, people thought visually - - they would draw diagrams and as they talked they would move their hands - - and I found this very attractive and I learned it. And it came naturally to me. But it was in my 30s that it really flourished. And I moved into the kind of physics where geometry helps. So it's now completely interiorised."

Prof. Berry's recollections suggest that, with practice and guidance, one can **learn** to be part of a visual culture even if one has an initial predisposition for a non-visual mode of thought. To quote Dennet (1990, p299), "conceiving of something complex" like a mathematical structure, is a matter of learning your way around, "a 'space' you must construct in your mind". By navigating through these conceptual spaces, one attains "conceptual fluency" (ibid.) However, "getting to that level of fluency can be very difficult" (ibid). In Prof. Berry's case, although this new visual culture came naturally to him it was ten years before "it really flourished", i.e. before he had truly attained "conceptual fluency". Having established the important role that computer simulations play in research, I will now address the issue of using computer simulations in communication, as promotional tools.

4.9 Just Pretty Pictures? Or Just Making Good Science Look Good?

Henderson tells us that:

> "For those engaged with drawing, painting, or mechanical drafting, how they see their world is strongly tied to the learned conventions of rendering it. Engineers who generate and manipulate visual renditions of objects do so using the conventions of drafting. But daily work is not school; work habits also play a major part in the construction of engineers' visual culture." (Henderson, 1995, p.198)

As mentioned in section 4.6.2, Henderson's work on the visual culture of engineers refers to renderings in perspective used to generate financial and organisational support for design and commercial promotion "drawn by illustrators, not engineers – who have been known to refer to them scornfully as 'pretty pictures.'" (Henderson, 1995, p.203). Some physicists and engineers receive similar scientific training, e.g. in the use of sketches, physical models, computer models, limiting case analysis etc. Thus, it is not entirely surprising a similar attitude towards 'pretty pictures' was expressed by three physicists who responded to my questionnaire.[88] Colourful renderings and nice visualisations, made with the latest computer graphics and animation technologies, are seen by some as superficial representations, used in a promotional capacity - either to generate financial and organisational support for their research, or to encourage an interest in physics among novices. **Phys_168** highlights the journal *Nature's* like of colourful visualisations remarking that: "... a nice (that means made with the latest computer graphics and animation technologies) visualisation is the best way to get grant money and/or publish something in journals like Nature." He added that: "computer simulation can be used both for serious research and nice-picture making." As Gooding notes, "the appeal of seeing via representations that *appear to depict* remains strong even when the objects depicted have no basis in any possible human experience." (Gooding, 2004b, p.16). This is illustrated by

[88] In fact, Phys,168 holds a BSc and MSc in Radiophysics and Eletronics, while Phys_215 holds a BEng in Electrical/Electronic engineering. We met Phys_215 in section 4.6.2 when discussing the disadvantages of computer simulations. He said computer simulations "can sometimes have a harmful effect - people get carried away with generating 'pretty pictures' and they can become lazy. Rather than seeking to understand, derive and simplify formulae, they just stick them into a program."

a recent controversy regarding the depiction of electron orbitals in the scientific journal *Nature.* (cf. Humphreys, 1999, Zuo et. al., 1999, Scerri, 2001). Similarly, **Phys_79**, who works on condensed matter physics, commented that: "Visualisation is just a very nice marketing tool for physics. It came as well fitted to the visualisation of complex systems fractals and old classical physics recently extending into chaos theories (e.g. the celebrated Mandelbrot pictures) but visualisation is meaningless for n-dimensional spaces Lie algebras in QM etc... " In these areas, physicists cannot abstract visual images from the world of sensory experience, they must rely on their theory to generate visual images of mathematical structures.

The use of computer simulations as so-called 'marketing tools' is not a trivial matter. It is an extremely important issue. In order to acquire funding, physicists first need to have their research understood, accepted, and published in peer reviewed journals, then in popular science magazines where they receive support of the educated and interested masses, and last but not least, by experts and non-experts who sit on funding boards. As the sociologist of science Bruno Latour remarks in his book, Science in Action (1987, p.104): " You may have written a definitive paper... but this paper will not become definitive if others do not take it up and use it as a matter of fact later on. You need <u>them</u> to make <u>your</u> paper a decisive one."

Computer simulations can be vital tools in enlisting support for one's research. In Fleck's (1935/1979) notion of discursive and material means of communication, facts are consolidated as knowledge in their translation from the language in which they are represented among specialists to language suitable for a lay audience. As Fleck put it: "Certainty, simplicity, vividness originate in popular knowledge... Therein lies the general epistemological significance of popular science." (Fleck, 1935/1979, p.115). Physicists use of computer simulations to market their research and consolidate facts as knowledge is an extremely important issue and worthy of further investigation. I raised this issue with Prof. Berry. He said:

> "... I **do** like pictures. I like them to look good, whatever the reason is for using them... [My view] is expressed very nicely in the title of the lecture that Felice Frankel gave... '*Making good science look good*'[89]... It's not a question of pretty

[89] Prof. Berry is referring to Felice Frankel's (2002) book "*Envisioning Science: The Design and Craft of the Science Image*" in which she discusses how she (an artist) works with scientists to make good science look good. When I interviewed Prof. Berry he had just returned from an **Image and Meaning** conference which Felice Frankel helped to organise. The title of Prof. Berry's talk was **Visual Thinking in Physics.** His contributors were George Barbastathis, David Kaiser (moderator) and Melissa Franklin

pictures implying some kind of triviality to impress somebody. I like my pictures to always look good, whatever the context." [90]

Prof. Berry's pictures have appeared in scientific journals, popular science magazines, and at *Science As Art* exhibitions. He has undoubtedly succeeded in making good science look good. In section 4.10 we will see how he has done this.

4.10 Presenting scientific pictures to experts and non-experts.

As mentioned in chapter 1, a central research question of this project concerns how analogies, but also computer simulations and images, are used in different contexts. For example, how they are used between experts, between experts and intermediates, and between experts and novices on informal and formal occasions. In the next chapter I will present findings from my on-line questionnaire on the various forms of analogies used in different contexts. In chapters 7 and 8 I discuss Dr. Lawson's use of analogies to communicate particle physics between experts in sub-disciplines related to the design of particle accelerators.

During my semi-structured interview with Prof. Berry I enquired into whether or how he changes his images when he presents them to different audiences, in different media. For example, to his colleagues in academic papers, to his students during lectures, to non-physicists in popular science magazines, and even to artists in competitions such as the *Visions of Science Photographic Awards*. I asked:

> "So you're using these images in quite different contexts: in academic papers, in popular science and then right into the art-science side of things. Ahm... how do you, sort of, tailor them to different audiences? Do the captions change? Or do the colours ever change?"

Prof. Berry explained:

> "... let's imagine I'm giving a lecture. Then for technical audiences I have pictures but I have all kinds of arrows pointing on them and I have little equations and little comments, labelling where the axes are and so on. When I present it to members of the

[90] The full quotation reads: "Well I don't do money. I mean I don't need much for what I do. The Royal Society supports my research and they give me more money than I need, it's not a lot. And as a theorist I don't require a lot. I **do** like pictures. I like them to look good, whatever the reason is for using them...Frankly I find it a fairly unattractive stance that somehow there's a slight - - implied in this view that you're reporting to me - - there's a slight sense of superiority - - that pretty pictures don't really have any place in science but these fools give you money so you might want to impress them. I have a completely different view - - completely. Which is expressed very nicely in the title of the lecture that Felice Frankel gave...'**Making good science look good**'. And that's a lovely title. And that's exactly the view I have. And the other way she expresses it, which again is exactly my thinking. Is that her project is called **Envisioning Science**. So that's the way I think about it. It's not a question of pretty pictures implying some kind of triviality to impress somebody. So I like my pictures to always look good in whatever contexts they are. The fact that some of my best pictures are published - - they're all published in scientific papers."

public, I sometimes use the same pictures but I strip out that technical stuff so there are no distractions. If I have to say something I'll say it in words. So that's the main difference. The pictures are often the same actually, interestingly enough, but it's the extra material that one puts in that does exactly that."

Prof. Berry subsequently furnished me with examples to illustrate this. In figures 4.9 and 4.10 below, he depicts conical refraction. When presenting it to an audience of experts he includes technical details that he is quite sure his audience will be able to absorb. For example, he locates and labels the focal image plane lying between the entrance face and exit face of the crystal, the radius of the light beam as it passes through the focal image plane and the radius of the cylinder of light as it emerges from the crystal. His three dimensional structure, consisting of shaded planes with clearly marked accompanying labels enables the expert viewer to easily identify the key components.

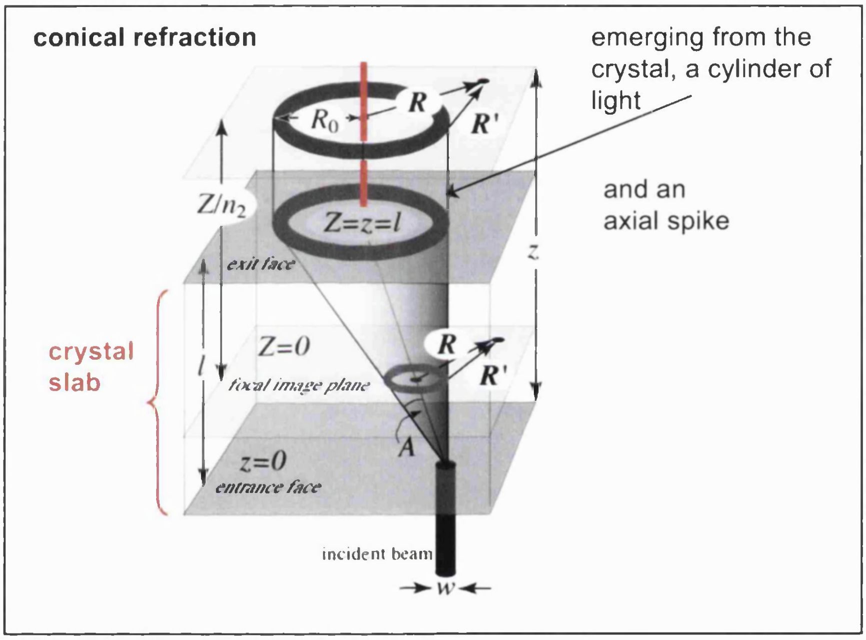

Figure 4.9: Example of picture Berry prepared for an audience of experts in his field.

In contrast, when presenting conical refraction to an audience of non-experts, Prof. Berry strips away all the technical details in an effort to ensure that the audience is not distracted nor over-whelmed by what they see before them. Thus, as you can see in figure 4.10 on the next page, the entrance face, internal focal plane and exit face are still identifiable but have not been labelled nor shaded separately. Prof. Berry employs red and yellow colours to good effect, making fig 4.10 more eye-catching and it's content more digestible for non-experts than figure 4.9. Prof. Berry is acutely aware of the communicative power of colourful pictures.

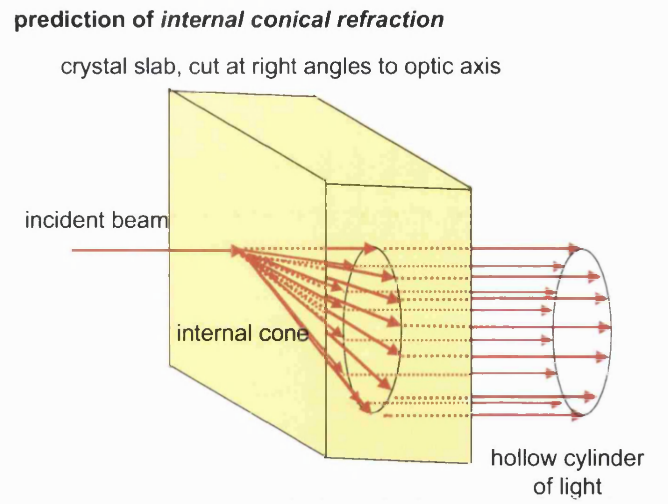

Figure 4.10: Example of picture Berry prepared for an audience of non-experts

However, he is also aware that the immediacy of his pictures may lead some non-experts to think that the pictures of abstract mathematical things are un-adulterated pictures of phenomena that exist in the physical world. Thus, Prof. Berry often deliberately uses artificial colours to prevent people from interpreting his pictures literally.

4.11 Berry's use of artificial colours to prevent a literal interpretation.

Berry's *Random Phases* picture (shown in figure 4.11 on the next page) won 1st prize in the *Science as Art* category of the *Visions of Science Photographic Awards* in 2002. The caption for the *Visions of Science Photographic Awards* tells us that *Random Phases* is a: Interestingly, Prof. Berry explained that he "submitted it as part of S*cience Concepts*, but the committee re-classified it as *Science as Art*… they say it was cheerful." To those who may wonder why he used such garish colours, Berry explains that he: "didn't want the colours to look natural, because they're not natural colours. And by making them completely saturated - - that's the technical term, there's no white in it - - it guaranteed that they looked artificial which is what I wanted… I wanted them to look artificial because I didn't want the system of visualization to be taken literally as a picture of something - - " One could contrast Prof. Berry's philosophically sophisticated approach with Richard Catlow's (1996) use of simulation-based visualization to 'model reality'.

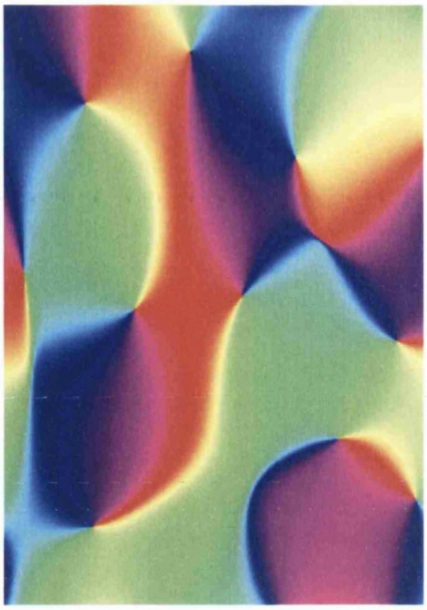

Figure 4.11: Random Phases, by Professor Sir Michael Berry.

This image won 1st prize in the *Science as Art* category of the Visions of Science Photographic awards in 2002.

http://www.visions-of-science.co.uk
Visions of Science caption reads: *"Computer generated image of the phases of several interfering waves travelling in different directions. Phase is colour-coded by hue. Points at which the colours meet are 'phase singularities', where the interfering waves cancel each other out."*

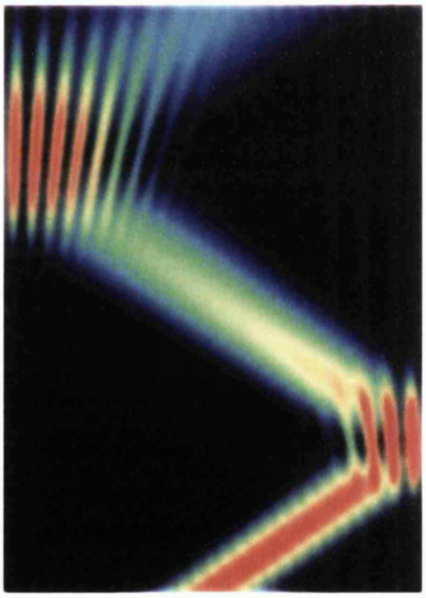

Figure 4.12: Bouncing & Spreading, by Professor Sir Michael Berry.

This image won 3rd prize in the Science Concepts category of the Visions of Science Photographic Awards in 2002.
http://www.visions-of-science.co.uk

Visions of Science Caption reads: *"Image generated by computer from the Schrödinger equation, illustrating wave-particle duality, a key concept in quantum physics. The image shows a wave, representing a quantum particle, bouncing between two walls (at the left and right sides of the picture) The probability of finding the particle is colour-coded, with red the most probable, and black the least probable. Initially the wave is localised and moving to the right (bottom of picture). It hits the wall and interferes with its reflection. Then the wave moves to the left and spreads before it gets reflected at the left wall and interferes again."*

4.12 Conclusions:

As I have shown in this chapter, there are some interesting findings on practicing physicists' experiences of using computer simulations as visualization tools in their research and as communication tools when presenting their work to experts and non-experts. I will now address each research question set out in the introduction of this chapter.

4.12.1 To what extent do these physicists employ computer simulations in their research?

In section 4.1 I showed that there was a skew towards using computer simulations as visualization tools, with 48.2% of the sample selecting between *"5"* and *"7/all the time"* on the 7-point scale. In fact, the largest single group, 22.7% of the total, selected *"7/all the time"*. However, as discussed in sections 4.3 to 4.5, some respondents pointed out that they did not use computer simulations primarily for visualization – they used them as means of calculating outcomes or designing equipment. The visual rendering of the output was often a useful by-product.

4.12.2 In what contexts do these physicists employ computer simulations?

An analysis of the qualitative replies revealed several common themes accounting for the prevalence of computer simulations in some areas and their paucity in other areas. In sections 4.2 – 4.5 I showed that computer simulations are often used if the research involves unusual geometries, several dimensions, numerous interacting parameters, huge search spaces, non-linear equations, complicated hardware design or experimental design, microscopic or extraterrestrial systems which are impossible (or extremely costly) to experiment upon. Computer simulations tend not to be used in areas that are easy to visualise (on account of the scale or the limited number of interacting processes), or, on the contrary, are at the edge of current theories because one lacks the equations and laws needed in the computer code. As I showed in sections 4.9 and 4.10, computer simulations are also particularly useful as a means of marketing physics: enlisting support from funding bodies, peers, and the general public by making good science look good.

4.12.3 What reasons do these physicists provide for not using simulations in their research?

In section 4.3 I explained that most physicists who made selections in the negative end of the scale when replying quantitatively to question 4, explained in their written comments that:

(i) they didn't "need to" use simulations as visualization tools because their work was easy to visualise;

(ii) they used simulations as "number crunchers" rather than visualization tools;

(iii) they did not have the time, funding or skills required to create simulations;

(iv) their work was observational, they dealt with "*real* data".

However, two physicists were dismissive of the value of computer simulations because in their view simulations promoted a 'cartoon view of reality' and replaced the real world with a 'virtual' one. But for the most part, respondents were of the opinion that the advantages of using computer simulations outweighed the disadvantages.

4.12.4 What are the possible disadvantages of employing computer simulations in research?

In section 4.6 I presented respondents written comments on the possible disadvantages of computer simulations. Many respondents stressed that computer simulations must always be used in conjunction with other physical methods, where possible. The models should constantly be matched with experimental data. The experimental data in turn should be tailored to the computer models in order to test its internal predictive ability. If one is simulating colliding galaxies, it is not possible to carry out 'real' world experiments, however the grounding physical assumptions made when building the model, should have empirical reliability where possible. Computer simulations are powerful discovery tools. They must be used cautiously, informed by studies of this kind that draws on practitioners' own experiences of what works and what doesn't work.

4.12.5 Do these physicists believe that computer simulations have strengthened physicists' visualization capabilities (a) in their own research area? (b) in physics in general?

As shown in section 4.4, a majority of respondents felt that computer simulations "definitely have" helped strengthen physicists' visualization capabilities both in respondents' **own research area** (51.6%) and **in physics in general** (52.5%). In section 4.5 I presented the main reasons given by respondents. To recap, I found that computer simulations:

(i) produce visual representations of complex geometries, which would be extremely difficult to mentally visualize;

(ii) allow one to follow the time evolution of complex systems; and to visualise solutions of equations;

(iii) exposure to complex geometries and evolving systems may help to strengthen one's ability to generate visualizations unaided by a computer;

(iv) computer simulations allow one to tweak parameters and probe functions systematically, allowing for greater understanding of the system.

(v) provide a laboratory with a type of control not possible in real physical systems. This virtual laboratory allows physicists to perform experiments that are too expensive, technically difficult or physically impossible to physically perform. Visualization is central in some of these instances and merely a by-product in others;

The minority of respondents who made selections on the negative end of the scale explained that computer simulations are used in numerical modelling, for example, **not** as visualization tools, but instead to calculate outcomes. Thus, they do not strengthen visualization capabilities. Also, they said computer simulations may have a negative affect on some individuals: acting as a mental crutch it may weaken their innate visualization abilities, making them lazy and discouraging them from pursuing analytical solutions.

4.12.6 Can computer simulations provide physicists with insights when conceptualising and communicating physics?

Many respondents were keen to emphasise that computer simulations offer little or no physical insight if they are used as 'black boxes' where the user has no knowledge of the internal predictability of the model or the mathematical foundations upon which the model is built. However, when used in conjunction with mathematical analysis, computer simulations can provide physicists with insights which deepen their theoretical understanding. In this chapter we've seen several examples of this. In particular, the experiences of **Phys_ 183, Phys_119,** and **Phys_89** discussed in section 4.7. In addition, interview material shows (cf. section 4.8) that Prof. Berry has made use of the generative power of computer simulations: highlighting surprising facets of the underlying mathematics which Prof. Berry came to understand in depth after conducting further mathematical analysis. In fact, Prof. Berry appears to have used computer simulations to further develop his **geometrical intuition** to the point where he has achieved **conceptual fluency** in navigating through abstract spaces constructed in the mind.

In chapters 5 and 6 I present data on my respondents' use of analogy to conceptualise their own research and communicate physics in different contexts. Then in chapter 8 I show how Dr. Lawson used analogies and synthesis to bridge conceptual divides between expert practitioners in sub-disciplines related to the design of particle accelerators. My research shows that, like computer simulations, good analogies can offer insights to experts, intermediates and novices, when conceptualising and communicating physics.

Chapter 5

Physicists' Use of Analogy to Conceptualise and Communicate Physics

"I quite often use the analogy of cold atoms to try to tackle problems in other areas. Cold atoms are a very clean and well understood research topic where I have experience in, and its results are widely applicable also to other areas."

Phys_35 [91]

"Kelvin-Helmholtz instability/ pouring cream into the coffee, intersection of two rivers, uprising cigarette smoke, turbulence causing stall of the airplane wings."

Phys_103 [92]

"The analogy of the gravitational mass quadrupole moment of a body, and its tensor of inertia."

Phys_120 [93]

"I am looking at a parallel plate resonator. The analogy I make is with a cheese sandwich and a stereo. The Cheese is the resonator, the Bread is the substrate and the Butter is the superconducting film under test. I apply a signal from a speaker to the cheese sandwich to build a standing wave (like you see when the tide is going out of an estuary) inside the cheese. Data is obtained by placing a microphone at the other end of the cheese sandwich. The amount of signal that is lost is mainly due to losses in the butter. In this way I can compare my cheese sandwich to other peoples cheese sandwiches."

Phys_193 [94]

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[91] **Phys_35,** a 33 year old, male, post-doctoral researcher, whose research interests include, "Cold atomic systems: degenerate Fermi and Bose gases; Bose-Einstein condensation; Atoms in lower dimensional systems (D<3); Quantum Information: Implementation of a quantum logic using cold atoms; Principles of non-classical light sources; Solid State Physics: Quantum Dot Materials; Vertical Cavity Lasers;"
[92] **Phys_103**: a 28 year old, female, research associate, whose research interests include, "Space Physics, satellite data analysis of the Earth's magnetosphere + numerical simulations."
[93] **Phys_120:** a 52 year old, male, senior lecturer in Physics, whose research interests include, "Gravity, Gravity gradiometry, Gravity Wave detection."
[94] **Phys_193:** a 31 year old, male, PhD student, whose research interests include, "High Temperature Superconductors, MgB2 Superconductors, Microwave Properties."

5.0 Overview:

This chapter focuses on physicists' use of analogy in their research. The data stem from the responses of 225 physicists to section 3 of my on-line questionnaire, follow-up e-mail correspondence with a select sample of 13 questionnaire respondents, and my semi-structured interview with Prof. Sir Michael Berry. I address the following research questions:

- To what extent do these physicists employ analogy in their research?
- To what extent do these physicists generate **original** analogies in their research?
- If they do not employ analogy in their research, what reasons do they give?
- Do these physicists use different forms of analogy in different contexts?
- What are the characteristics of a good analogy?

I should out at the outset of this chapter that these physicists are not necessarily representative of the entire community of physicists in the UK and Ireland. They probably chose to respond to my questionnaire because they had a particular interest in the role of visualization and/or analogy and/or computer simulations in the conceptualisation and communication of physics. However, my as my main aim is to explore the various forms of analogy employed in different contexts, it is actually advantageous to have a sample which has much experience of using analogy to conceptualise and communicate physics. The views of these 'analogy enthusiasts' are balanced by the views of physicists who were prompted to respond to the questionnaire because they were interested in issues surrounding visualization and/or computer simulations. Thus, I believe that the range of responses obtained via the on-line questionnaire is extremely valuable.

In this chapter I will show that there was a skew towards using analogy in research but not towards generating original analogies. Thus, most respondents recognise that their analogies are drawn from a stockpile of analogies which already exist in their respective research areas. Some respondents appeared to hold a narrow interpretation of analogy that excluded formal, mathematical analogies. I suggest that some branches of physics may be more open to the use of analogical reasoning than others. I also uncover certain journals' apparent censorship of creative language. I question the usefulness of this interventionist approach if it is clear that a physicist is using intelligently constructed, creative language, as a means of marketing their research to peers in order to enlist support.

5.1 Ambiguity Over How to Define Terms Like Research & Analogy

By my definition 'research' consists of a blend of private cognition and public communication: data interpretation, theory generation, experiment design, hypothesis testing, scientific discovery, literature reviewing, physics-based conversations with colleagues, presentation of one's work at conference level, etc. However, the 'public' or 'official' view of research emphasises the external, systematic and technical aspects, over the personal, mental, interpretative aspects. It is not particularly surprising then that some questionnaire respondents experienced difficulty interpreting what I meant by the term 'research'. For example, in response to Q3 *"Do you use analogies in your research?"* **Phys_224**, a 34 year old, female, post-doctoral research associate, whose research interests include "modelling solar cells" indicated that she sometimes (i.e. 4 out of 7) used analogies in her research. She provided two examples: "Flow of water for current carrier dynamics. Elastic band three dimensional grids for atomic lattices." When asked in *Q.3d "If you don't use analogies in your research, is there a specific reason why you don't"?* She replied: "(Not sure about this question). The above analogies I use to help me think about and explain to others what I might be thinking, I don't use them in the research as such." (ibid.) Thus while **Phys_224**'s comments fit with my own definition of 'research' she appears to interpret 'research' as being similar to that which is presented in scientific journals, where the scaffolding used in the early stages of cognition is usually edited out of the texts.

Literature in the History and Philosophy of Science, Cognitive Science, Science & Technology Studies, and Science Education suggests a broad interpretation of the term *analogy*. Holyoak and Thagard's (1995) comments provide a good summary:

> "Scientific analogies have at least four distinguishable uses: discovery, development, evaluation, and exposition. The most exciting is discovery, when analogy contributes to the formation of a new hypothesis. After a hypothesis has been invented, analogy may contribute to its further theoretical or experimental development. In addition, analogy can play a role in the evaluation of a hypothesis, as revealed in the arguments given for or against its acceptance. Finally, analogies are often used in the exposition of science, when new ideas are conveyed to other people by comparing them with old ones." (Holyoak & Thagard, 1995, p.189)

However, as outlined in chapter 2, data from the on-line questionnaire indicated that many physicists have a much narrower interpretation of what constitutes an analogy. It is as though the term *'analogy'* has been contaminated though its associations with poetics, popular science, politics etc.[95] For many physicists, metaphor, and to a lesser extent analogy, are synonymous with ambiguity, inaccuracy and dangerously seductive simplicity; they believe that physicists must be wary of being misled by these incomplete descriptions of the world. Thus, many of the physicists who propound this view would probably <u>not</u> share science writer Martin Krieger's views that:

> "... to accuse the physicist of employing everyday models and metaphors is no more interesting to the physicist than accusing the novelist of writing fictions and employing genre conventions... " (Krieger, 1992, p. 100)

While most respondents happily admit to employing analogy as a pedagogic tool when communicating physics with novices, many physicists are keen to emphasise that they use something "stronger than analogies" in their research. For example, **Phys_185** (a 45 year old, female research fellow, whose research interests include quantum computing, quantum many body physics, phase transitions, and physics of information) explains: "What I use is often stronger than analogies, in that the underlying mathematical description is the same or similar in the first approximation. For example, harmonic waves appear all over the place in very different physical situations." [96] This description is in line with what Hesse (1974) terms *'formal analogies'*. According to Hesse (1974, p.90) the function of formal analogies is: "to aid the imagination in understanding formal relationships, and to enable transfer of mathematical results from one system to another irrespective of subject matter." Thus, some physicists, while wishing to distance themselves from the term *'analogy'* were actually providing examples of what would be termed *'formal analogies'* in the fields of history and philosophy of science, and cognitive science. However, it is not surprising that practicing physicists were slightly uncertain how to interpret or define the term 'analogy': there is no standard meaning for the term; it varies both within and across the cognitive-historical-psychological disciplines (c.f. Hesse, 1974, p.92)

Phys_221 (a 24 year old, male PhD student involved in quantum computing) offers excellent understanding into the difficulty physicists have in interpreting the term *'analogy'* as he explains in the *Additional Comments* section of the questionnaire:

> "Analogies in physics tend to take two different forms. One is close the usual meaning, i.e. this thing is 'like' that thing, maybe it will behave the same. In these cases, the analogy would give an idea, which is then later tested with rigorous maths. The other form of analogy is where the same maths can be used to describe two situations. In this case the meaning of 'analogy' is much stricter: any phenomena in

[95] In fact, use of the term 'metaphor' was deliberately avoided after pilot studies found that it had negative, 'fluffy' connotations for some physicists.
[96] Other physicists referred to harmonic waves and LCR circuits as exemplary analogies however.

one situation _will_ have a counterpart in the second, as the maths for the two is identical. The analogy allows you to use the physical picture attached to one to visualise the other. A good example is the use of spin-1/2 systems to represent any two level system. A superposition of two atomic levels can then be thought of as the spin pointing in the x or y directions." (Phys_221)

Phys_221's description sounds similar to Nersessian's (1992a, p.17) account of Maxwell's view of analogy. She tells us that: "According to Maxwell, a physical analogy provides both a set of mathematical relationships and an imagistic representation of the structure of those relationships drawn from a 'source' domain to be applied in analysing a 'target' domain about which there is only partial knowledge."

The difficulty in defining analogy was also underscored by the comments of **Phys_190**, a 44 year old, senior lecturer in physics and astronomy. She was uncertain whether or not she employed analogy in her research because some of the examples of analogy provided in the questionnaire were not, to her mind, analogies, but, "a shorthand description of a specific set of mathematical assumptions." In the *Additional Comments* section of the questionnaire she put forward her alternative perspective saying:

"Not sure I agree with some of your examples of 'analogy in research'. A 'billiard ball model' isn't to my mind an analogy - it's a shorthand description of a specific set of mathematical assumptions. The same goes for the cosmic string vs guitar string"

In her experience, analogies are: "very seldom helpful *in the research* (but very useful when explaining research to outsiders, e.g. giving talks to astronomical societies - I use analogies all the time then)." She added a note of caution, saying: "Getting too wedded to analogy in research can be dangerous, since analogies are seldom precise."

Thus, in follow-up email exchanges with a select sample of questionnaire respondents, I pursued this issue, asking whether analogical reasoning is *"regarded as a modelling activity that constitutes a substantial method of scientific innovation?"* **Phys_2**, a PhD student, whose research interests include: "Vertical cavity devices, communications, high output devices," said, "yes, analogies are a very important factor in both understanding and learning, it can make even the most specialised of topics open to all." **Phys_202**, a senior lecturer in geophysics also said "yes" because in his experience it "allows us to try to explain in simple physical terms what is happening, and in perhaps taking developments from one area of endeavour to another." **Phys_185,** who had said in the on-line questionnaire that what she uses is "often stronger than analogies, in that the underlying mathematical description is the same or similar in the first approximation" said in a follow-up e-mail, "I think I interpreted 'analogy' more narrowly than you intended."

It is from comments like these that I have concluded that many respondents appear (initially) to hold quite a narrow interpretation of analogy, excluding abstract, mathematical analogies - what Hesse (1974) would call formal analogies. In this chapter and the next I show that different forms of analogy are employed by physicists in different contexts and that the appropriateness of the analogy depends especially on the level of expertise of the target audience and the tone of the discussion.

5.2 Degree to which respondents use analogy in their research.

As discussed in chapter 2, section 3 of the on-line questionnaire opened with this statement:

"Some physicists use analogy in their research.
- e.g. using a billiard ball model when considering the movement of charge through a solid;
- e.g. comparing ultrasonic transmission down a rod, to an electrical transmission line;
- e.g. comparing the vibrations of a 'cosmic string' to the vibrations of a guitar string;
- e.g. Schrödinger's equation is derived by using Hamilton's mathematically unified treatment of geometrical optics and analytical mechanics;
- e.g. Sheldon Glashow has remarked that he 'was led to the group SU(2) x U(1) by analogy with the approximate isospin hypercharge group which characterises strong interactions'."

In an effort to encourage respondents to take a broad interpretation of 'analogy', the exemplar analogies ranged from simple, pictorial analogies to more complex and abstract, mathematical analogies. The first two examples were given by physicists who contributed to my master's dissertation (Muldoon, 2002); the third is derived from Brian Greene's best-selling popular science book *The Elegant Universe (1999);* the fourth is from a paper in the **European Journal of Physics** (Tzanakis, 1988); the fifth is extracted from Sheldon Glashow's Nobel Lecture (Glashow, 1979).

Respondents were then asked: *"Q3. Do you use analogies in your research?"* As indicated by Figure 5.1 on the next page, the use of analogy in research was widespread among the physicists who responded to the on-line questionnaire. 52 respondents (23.1% of the sample) said they use analogy "all the time/7" in their research. This is over three times as many as those that claimed to *"never/1"* use analogy in research. As mentioned at the outset of this chapter, I do not wish to generalise from this sample to all of physics. I will use the quantitative and qualitative data to provide a much needed account of the forms of analogy used by physicists in different contexts.

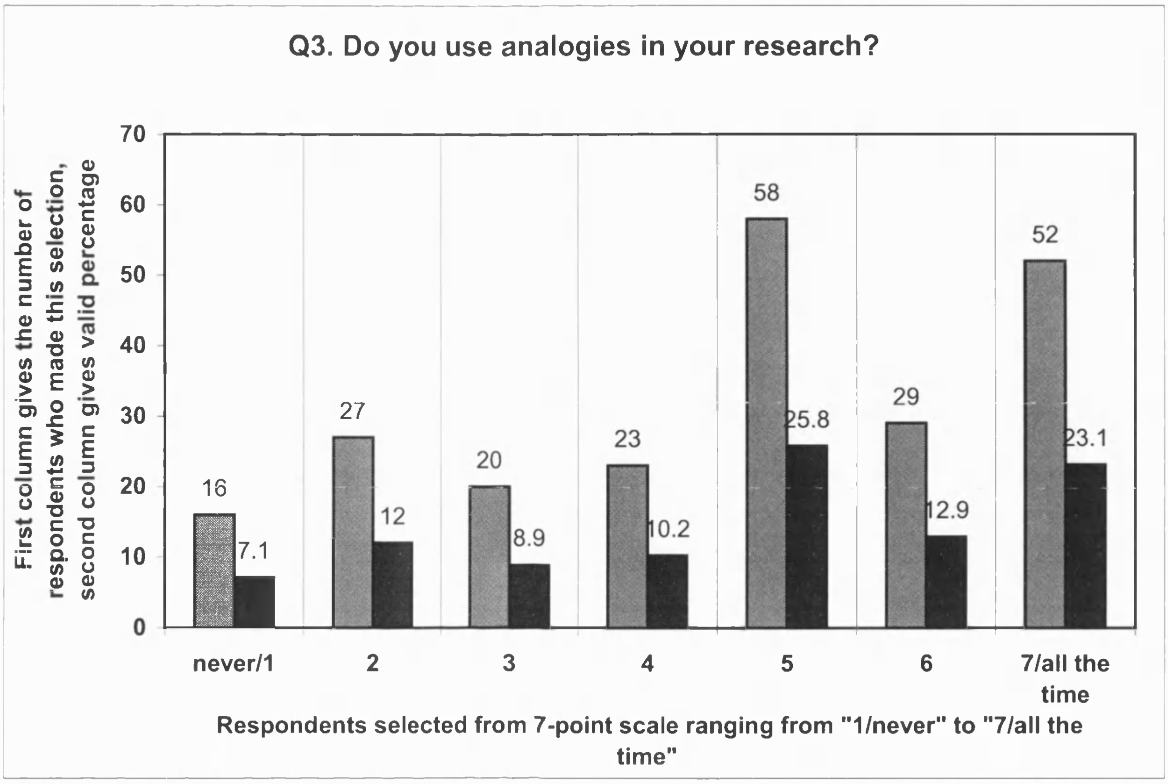


Figure 5.1: Chart showing the degree to which respondents employ analogies in research

5.3 Reasons given for not using analogy in research.

The physicists who did not use analogy in their research gave the following reasons:

5.3.1 Not necessary as work is already imaginable:

For many respondents, the use of alternative problem solving and visualization techniques makes analogy unnecessary. For example, **Phys_13**, a lecturer involved in "far-infrared optics, microwave background astronomy, telescope design," said, "much of it is classical - straightforward to imagine" Similarly, **Phys_34** said: "Most of my work can be seen visually as an outflow from a star so there are no advantages to using an analogy." **Phys_65,** a senior lecturer, said: "The work I'm doing directly is building and testing equipment [a particle detector for the Large Hadron Collider]. I don't need analogies to understand it."

5.3.2 Too difficult to formulate:

On the other hand, some respondents said that the nature of their work means that analogies are difficult to formulate. For example, **Phys_18**, a 43 year old research associate, whose research interests include: "high energy astrophysics, stellar evolution in particular massive stars, starburst regions" said, "it is often too difficult or not very useful to formulate appropriate analogies that describe a certain problem." In the experiences of **Phys_ 143**, a 22 year old, PhD student: "The 'emergence' of superconductivity from simple systems means that making analogies is more effort than not."

5.3.3 Only use 'analogy' when explaining research to non-specialists:

Phys_82, a 24 year old, research associate, whose research interests include, "optical interconnects, optical computing, computer memory," said in his experience, you "don't tend to use analogies in day-today research as your colleagues should be able to grasp the concepts with out them, its more needed when talking to non-colleagues." Similarly, **Phys_123**, a 47 year old, Professor of Physics, whose research interests include molecular spectroscopy, said: "I use it more in explaining my research to others (particularly non-specialists)." Thus, for some physicists analogy is most appropriate and useful when communicating their research with novices, rather than with peers. However, one should consider the possibility that these physicists may not have been thinking of analogy in the sense of abstract mathematical analogies that other respondents mentioned using in their research. Instead they may have been thinking of analogy in a simplistic sense, as it is often used in popular science books for example.

5.3.4 Analogies are too simplistic and can be misleading:

The string theorist (and prize-winning popular science author) Brian Greene tells us that, "if you relentlessly stretch a rubber membrane, sooner or later it will tear. This simple fact has inspired numerous physicists over the years to ask whether the same might be true of the spatial fabric making up the universe." (Greene, 1999, p.265) In Greene's experience, "These images have considerable explanatory power; they are used regularly by physicists as a visual guide in their own technical work." (ibid. 376). However, Greene acknowledges the dangers of over-extending the analogy and asks, " … can the fabric of spacetime rip apart, or is this merely a misguided notion that arises from taking the rubber membrane analogy too seriously?" (ibid, p.265) Although analogies can be particularly useful when dealing with concepts far beyond perceptual experience, such analogies can be misleading if taken too far. Therefore it is not surprising that some questionnaire respondents were overtly wary of analogy, saying it was too simplistic and misleading to be of use to them. However, as with section 5.3.4 above, it is not clear how they interpreted and defined 'analogy'. **Phys_111**, a research student who deals with "Epitaxial Systems, Non Equilibrium, Probabilistic Description," said he "Seldom use[s] analogies unless the similarities are uncanny. Often analogies are taken too far." He distinguished between analogies and simplifications (as Phys_190 did) saying that, "a simpler description of the system is not an analogy, but a simplification. There are however, direct analogies, e.g. Mass, spring, damping is completely analogous to LCR circuits." He concluded by saying that he "prefer[s] to deal with simpler versions of the system instead of divorcing it from its context."

Similarly, **Phys_146,** a 43 year old, Senior Lecturer, whose research interests include, "Nuclear reaction mechanisms" said: "I'm not especially keen on analogies because I prefer to focus on reality and stay with what is actually happening, or as close to it as I can get, rather than going off track to something similar and perhaps simplistic." **Phys_146's** comments suggest a realist stance. However, as her research interests are in "nuclear reaction mechanisms" this prompts two questions: Firstly, do she and her colleagues not employ various phenomenological models, founded on formal analogies – the liquid drop model, the shell model, the compound nucleus model, the optical model – in order to describe scattering, fission etc.? Perhaps such formal analogies are "taken for granted", as **Phy_128's** experiences in condensed matter physics suggest. [97] (cf. section 5.6). In his view, "in builders' terms, in an established field the analogy is not the scaffolding, but the foundation." Secondly, doesn't the 'correct' experimental set up sometimes produce 'unrealistic' (but useful) results that may not exist outside the laboratory? (cf. Morrison, 1999, p.45). The type of model one uses to represent something depends upon the problem in question. For example, one may use two different models to represent water: (i) Diffusion or Brownian motion: which regards water as a collection of molecules; (ii) Water flowing through pipes: which regards water as a continuous fluid. Depending on one's goals, either model could prove enlightening for a particular problem. **Phys_146** may not have been thinking of formal mathematical analogies (though examples were supplied in the questionnaire) when she responded in this manner.[98]

[97] "Here a simple analogy between electrons in crystals and atoms in standing light waves caters for, say, 10-20% of the current theoretical research in condensed-matter physics. The pioneering work was to discover this analogy and to demonstrate it in experiments, the rest is follow-up and less original where the analogy is taken for granted." (Phys_128)
[98] Although clarification on this issue was sought from Phys_146 in a follow up e-mail, no reply was received.

5.4 Degree to which respondents generate original analogies.

Question 3b of the on-line questionnaire asked: *"If you do use analogies in your research, how often do you generate original analogies?"* The quantitative responses are plotted in figure 5.2 below.

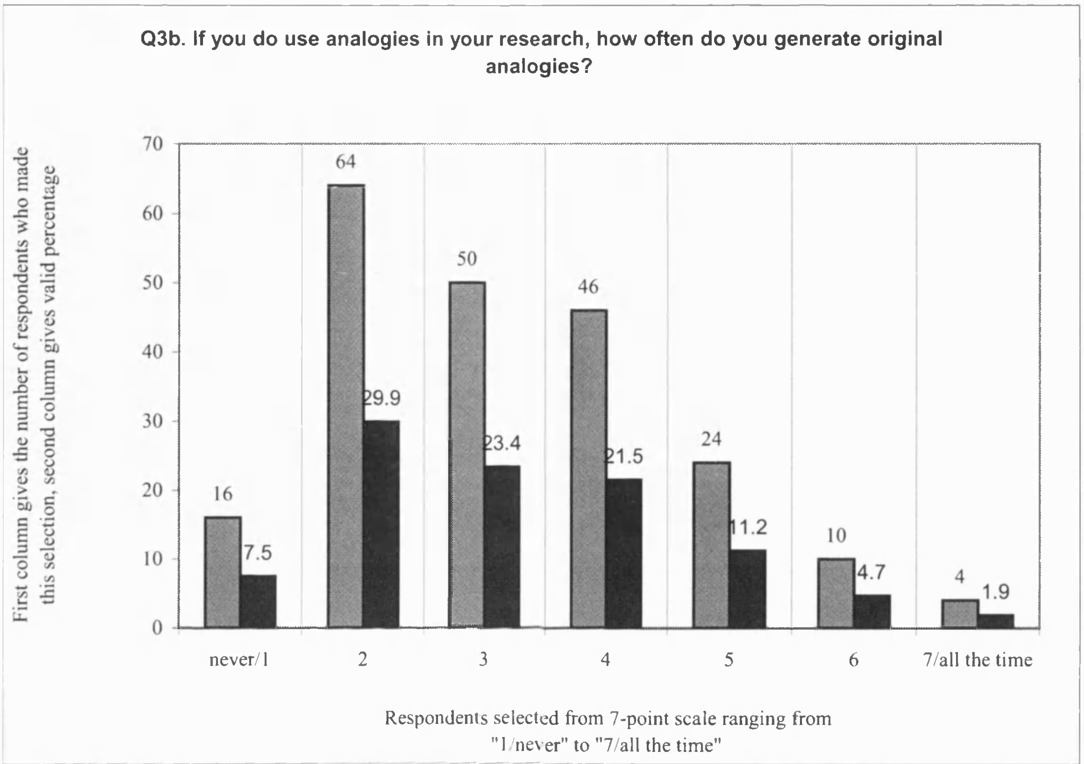


Figure 5.2: Chart showing degree to which respondents generate original analogies in research.

In figure 5.1 we saw that **61.8%** of respondents selected between *5* and *7* when commenting on the degree to which they use analogy in research. However, as shown in figure 5.2, when commenting on the degree to which they generate original analogies, **60.8%** selected between *1* and *3* (and 82.2% selected between *1* and *4*). Thus, a majority of respondents are aware that they mostly use an existing stockpile of tried and tested analogies. This finding is not particularly surprising. The pilot study suggested that physicists realise that they often rely on a stockpile of conventional analogies. As Krieger (1992, p.74) notes: "To do physics, one participates in its practices, culture, and ideology, thus employing the conventional models and analogies." However, as discussed in chapter 1, reasoning by analogy is an iterative process, involving considerable re-structuring, prior to solution. As Nersessian (1995) points out:

> "Of course, there are cases in which a direct analog representation for a problem exists, and substitution and mapping is all that is required. But, more often,

> substantive changes need to be made to the analogical source in order to fit the constraints of the target problem." (Nersessian, 1995, p.207)

Similarly, Holyoak and Thagard (1995) argue that:

> " The most cognitively complex origin of a source comes when it is not noticed, retrieved, or compiled, but must be constructed. Construction may involve aspects of the other three processes but goes beyond them in the extent to which the source is different from anything that was known to the scientist..." (1995, pp. 193-194)

According to Holyoak and Thagard, to understand the use of analogy in science, it is important to realise that "selection of source analogues often involves very complex designs and constructions that go beyond simple recall of past cases." (ibid.) Visual representations often play an important part in the construction of productive source analogues. These can be in the form of "mental images, diagrams on paper, or both." (ibid.) Thus, generating original analogies would appear to be cognitively more complex than noticing analogies, although the latter task is not trivial either.

Some physicists were confused over how one could know whether or not one's analogy was 'original' if it had not been published. For example, **Phys_18**, a 43 year old research associate said she never used analogies in her research on "high energy astrophysics, stellar evolution in particular massive stars, starburst regions" because, "it is often too difficult or not very useful to formulate appropriate analogies that describe a certain problem." In the additional comments section, she explained that she:

> "found the part on analogy not so easy to answer. Although I may use analogies for myself in order to understand a problem I think I have never used it in a proper publication so I cannot tell whether I have produced original analogies" (Phys_18)

Question **3b** was intended to promote self-reflection, to enquire into whether analogies generated in the early stages of research actually make it into physicists' personal notebooks, discussions, lab meetings, presentations and scientific articles. The hypothesis was that they do not, unless the similarities are uncanny and rigorously tested. It is unclear whether **Phys_18** is questioning the "production/publication" aspect of generating original analogies in her research, or the "originality" aspect. Her additional comments seem to contradict her response to Q3d. The objective was not to focus on originality in a copyright sense, but to see the extent to which physicists are creative at dreaming up/ composing/building/generating/seeing analogies in their work; as a poet, musician or painter might do in their work. **Phys_18's** uncertainty probably revolves around whether she was learning something new to her or generating something that is new to everyone. As mentioned in section 1.5 Gardner (1993) calls this 'big-c' Creativity and 'small-c' creativity, where many people exhibit small-c creativity but only a few are big-c Creative.

Similarly, Csiksszentmihali (1988) identifies two forms of creativity: personal creativity, i.e. where an individual regards the product of their own work as creative; and social-cultural creativity, i.e. where others within the same society and culture regard the product of an individual's work as creative (cf. Yu-Tung Liu, 2000, p.267).

5.4.1 Examples of Original Analogies Used By Physicists' in Their Research

The examples of original analogies offered by **Phys_63** and **Phys_193** (shown in table 5.2 below) are similar to what Dunbar (1999) would call *long-distance* analogies, where the scientist maps from a commonplace *source domain* (a snickers bar or a cheese sandwich) to a more specialised target domain (a bar-shaped galaxy or a parallel plate resonator). This kind of mapping allows one to remember a key point in a very simple way. It acts a scaffolding or framework with which to explain one's concept. In my system of classification (which I will discuss in detail in section 5.5) these examples are playful analogies, expressed verbally/pictorially/physically, with low systematicity. Whether or not these original analogies are produced in popular science magazines or scientific journals depends on in-house style, or conventional norms respectively. As **Phys_9**, a lecturer in physics and astronomy explained in the on-line questionnaire's section on science communication: "Analogies may be perceived as a dumbing-down, humorisation or over-simplification of a concept; therefore they need to be used with care if the audience is already expert or 'stuffy'." **Phys_63** has used his "snickers" analogy in the title of conference papers. This may be because the field of cosmology is more open to the use of playful analogies than other fields (cf. Muldoon, 2002). This issue is something I pursued in follow-up e-mail exchanges with a selection of questionnaire respondents (see section 5.7). The educational value of using analogies which map from a commonplace but implausible source to a specialised target is discussed in the next chapter.

ID	Q3. Do you use analogies in your research?	Q3b. If you do use analogies in your research, how often do you generate original analogies?	Q3c. If possible, can you offer an example of an analogy you use/ have used in your research?	Q3d. If you don't use analogies in your research, is there a specific reason why you don't?
Phys_63	5	4	Likening the shape of the "bar" structures found at the centres of some galaxies to a peanut in its shell (hence the "Snickers hypothesis" that there is a peanut in every bar...)	
Phys_134	3	2	In 1996, I had a mental image of a stadium; this image was helpful for describing properties of D0-branes interactions	I am not intelligent enough
Phys_157	7	5	High energy physics experiments are vast. They are broken down into smaller components. One area of my research is pattern recognition and in order to solve the complex interconnectivity of the objects I was forming so that they could be categorised and classified I invented the analogy of an interconnection network of nodes for these objects.	
Phys_193	7	7	I am looking at a parallel plate resonator. The analogy I make is with a cheese sandwich and a stereo. The Cheese is the resonator, the Bread is the substrate and the Butter is the superconducting film under test. I apply a signal from a speaker to the cheese sandwich to build a standing wave (like you see when the tide is going out at of an estuary) inside the cheese. Data is obtained by placing a microphone at the other end of the cheese sandwich. The amount of signal that is lost is mainly due to losses in the butter. In this way I can compare my cheese sandwich to other peoples cheese sandwiches.	N/A

Table 5.1: Examples of Original Analogies Used By Physicists' in Their Research

5.5 Frequency of occurrence of different forms of analogy

A marvellously diverse range of analogies was provided by the physicists who responded to the on-line questionnaire. In total, 147 examples of analogies were given, ranging from analogies with superficial relations to analogies with deep, structural relations. Many of these examples were drawn from the usual stockpile used in physics textbooks (current flow as analogous to water flow; LCR circuit analogous to harmonic oscillator), however there were also many specialised analogies. (See A5.1 for examples supplied by respondents who said they use analogy all the time in their research). These 147 examples of analogy were sorted according to three basic forms, as shown in figure 5.2 below. Set **A** indicates that there are 50 examples which could be classified as verbal or pictorial or physical analogies, used by physicists either in playful exploration of new ideas during private conceptualisation and informal communication with colleagues; or to make physics accessible and entertaining to novices. Set **B** indicates that there are 90 examples that could be classified as physical or pictorial analogies, used by physicists to provide physical and pictorial insight in conceptualisation and communication in formal and informal contexts. Set **C** indicates that there are 45 examples which could be classified as mathematical analogies, possessing a high degree of systematicity – i.e. a hierarchy of deep, structural relations. These analogies are used by physicists as tools of exploration in private conceptualisation and when communicating with peers in informal and formal settings. They are almost never used with novices, as both the source and target domains would be unfamiliar to them.

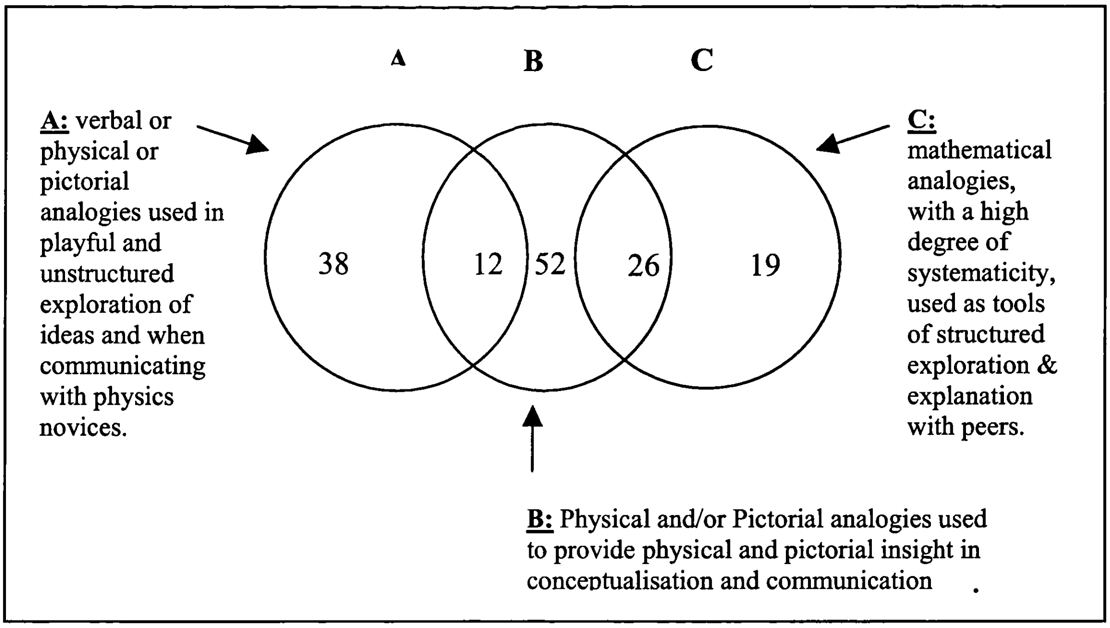


Figure 5.3: Venn Diagram showing that the 147 examples of analogy offered by respondents were sorted into three sets A, B, C according to form, function and context.

The overlap between **A** and **B** indicates that many playful analogies have physical and/or pictorial components, e.g. "Modelling electron transport through nanocrystalline TiO2 as 'hoppers' walking randomly through a cubic lattice." **(Phys_69).** The overlap between **B** and **C** indicates that most of the mathematical analogies supplied have pictorial and/or physical components. For example, the "physical picture of the density matrix by using the Bloch vector analysis." **(Phys_218).** Analogies of a more abstract nature may have not been as easy to express through the medium of a questionnaire and may therefore have been omitted in favour of more expressible analogies. A table summarising the forms of analogy employed in different contexts is presented on the following page.

The analogies in set **A** contain concepts drawn from everyday experience and are thus accessible to novices. The analogies in set **B** contain an intermediate range of concepts, descriptions and processes, and consequently are accessible to those with some physics education. The analogies in set **C** are more technical and specialised, and are therefore accessible to experts, some intermediates but few novices. Thus, from the venn diagram (figure 5.3) we can see one reason why set **B** contains the majority of analogies: the analogies in this set are <u>accessible</u> and <u>appropriate</u> to a broader range of contexts, as the set overlaps with the domains of experts, intermediates and novices. To use the terminology of literary theory, the analogies in set **B** have greater 'addressivity'. I introduce the Bakthinian concept of speech genres and addressivity in section 6.2 and discuss the key factors which affect physicists use of analogy when communicating with different audiences in different contexts. It will become clear in chapters 6, 7 and 8, why I make these claims about the use of analogy to communicate physics to non-physicists. However, I felt it would be useful to include it here in order to clarify the forms of analogy used in scientific research.

Thus, from the myriad of examples provided by respondents, one can see some evidence for Nersessian's assertion that: " … analogies are not 'merely' guides to thinking, with logical inferencing actually solving the problem, but *analogies themselves do the inferential work and generate the problem solution.*" (Nersessian, 1992a, p.20, italics in the original).

Expressed As	Set A: Verbal or Physical or Pictorial Analogies	Set B: Physical and Pictorial Analogies	Set C: Formal, Mathematical Analogies
Systematicity	Low	Medium to High	High
Definition	The analogies are often novel and amusing, relating abstract physics concepts to familiar, everyday things like dazed chickens, cheese sandwiches, Snickers bars, football stadiums, donuts, etc.	The physical picture attached to one situation can be used to visualise another. These idealised pictures are usually used iteratively: further refined and abstracted through rigorous mathematical and experimental testing.	The same mathematics can be used to describe two situations. Phenomena in one situation will have a counterpart in the second, as the mathematics for the two is identical.
Example	"A Tokamak is like a donut, but filled with plasma instead of cream." [Phys_189] "Reversal of magnetisation through a magnetic logic NOT-gate likened to a car performing a three-point turn." [Phys_191]	"Cerenkov light is created when a particle passes through matter at above the local speed of light. The effect is similar to the shock wave created by an airplane flying at above the speed of sound." [Phys_198]	"I quite often use the analogy of cold atoms to try to tackle problems in other areas. Cold atoms are a very clean and well understood research topic where I have experience in, and its results are widely applicable also to other areas." [Phys_35]
Often rely on	Popular associations; Creative imagination;	Geometrical intuition Kinaesthetic awareness (of macroscopic capacities); Tacit knowledge (gained through experimentation);	Geometrical intuition (seeing patterns and symmetries in the underlying mathematics)
Functions **(Epistemological Aims)**	Tools of Explanation. To make physics accessible, memorable and entertaining, in order to enlist support. Occasionally used by expert physicists in private conceptualisation to play with ideas.	Tools of Exploration; Provide physical and pictorial insight; Mechanisms *underlying phenomena in analogous* systems can be compared & contrasted.	Tools of Exploration; Allow direct comparison of physical systems to be made on an abstract mathematical level. Basis for computer simulations;
Contexts of Use	(1) Private Conceptualisation;	(1) Private Conceptualisation;	(1) Private Conceptualisation;
	(2) Expert-Expert Communication in **very informal** settings; Often used to entertain an audience of experts or to make a point in a lively debate amongst peers;	(2) Expert-Expert Communication in **formal** & **informal** settings; Use in journal publications is dependent on norms of research area and "in-house style" of journal. Some journals object to creative use of language.	(2) Expert-Expert Communication in **formal** & **informal** settings, including journal publications & presentations to conferences of experts;
	(3) Expert-Intermediate Communication in **informal** settings (used to entertain and offer insights);	(3) Expert-Intermediate Communication in **formal** and **informal** settings;	(3) Expert-Intermediate Communication in **formal** and **informal** settings;
	(4) Expert-Novice communication (to make physics accessible and memorable by drawing on concepts from everyday life);	(4) Expert-Novice communication (in particular to visualise the unseen, e.g. atomic physics, nano-physics, cosmology and astrophysics, etc.);	(4) Almost never used by physicists to communicate with novices as concepts from the source domain would be unfamiliar to novices.

Table 5.2: Summary of Different Forms of Analogy Employed in Different Contexts.

5.6 Do analogies form the scaffolding or the foundation in research?

As discussed in the literature review, Dunbar (1999) found that, amongst the biologists he studied, analogy was used as scaffolding and often discarded and forgotten after it had served as a bridge when building new explanations and models. In order to explore how analogies evolve in the course of theory building and disseminating ideas to the scientific community and the general public, several questionnaire respondents **(Phys_202, Phys_19, Phys_2, Phys_193)** who were all enthusiasts for using analogy in their research were asked the following question in a follow-up e-mail:

> *"Q. In your research, do you use an analogy as scaffolding, often discarding and forgetting it after it has served as a bridge when building new explanations and models? Or do the analogies you use in the early stages of your research usually make it into your personal notebook (or equivalent) and then into your research papers, perhaps in an adapted form?"*

Phys_202, replied to the follow-up question saying: "It can go either way. If it has served its purpose but has become limiting in its application, then it gets discarded. If however it is still serving a useful purpose, then it is retained. Either way, it sometimes does make it into notes and papers, often amended or altered to suit." In the on-line questionnaire he had said that he very often (i.e. <u>6</u>/7) uses analogy in his research but rarely (i.e. <u>3</u>/7) generates original analogies. In the questionnaire, he gave the following analogy as an example: "Smoke rings to describe the flow of currents induced in the ground by the rapid turn-off of a current in a transmitting loop on the surface. First proposed by Misac Nabighian, but very useful. I use it in both teaching and research." Also, in the on-line questionnaire he had said he very rarely (i.e. <u>2</u>/7) finds it difficult to get a mental picture of the physical processes involved in his research. In his words, "I seem to have an ability to visualise the objects and the fields in both 2 and 3 dimensions. I first realised this, consciously, when I had just started my PhD. I could see' the object that was generating an anomalous response, just from the shape of the response." When he does have difficulty getting a mental picture of the physical processes involved in his research, he said: "I try to pare the problem down to its simplest elements, or to in a sense transform it to something similar but simpler." This is where analogy comes in. This tool of exploration can be used in a structured way to map ideas from one area to another, thereby extending one's knowledge.

Phys_19, a 60 year old Professor of Theoretical Physics did not address the "scaffolding" issue in his response to the follow-up query, but instead focused on the physical aspect of reasoning by analogy, saying: "it is important to think physically in all our work: deriving formulae, doing calculations etc. It is otherwise very easy to make an error or a faulty judgment. To give a simple example, it is important to check a computer code using known (high or low) asymptotes." In the on-line questionnaire, he had said he never (i.e. 1/7) has difficulty getting a mental picture of the physical processes involved in his research because of his "Excellent visuo-spatial iq." (Unlike most respondents he has a BA in mathematics). He also said that he uses analogy "all the time" in his research, e.g. "particle sliding on the surface of a tapering cone so that the azimuthal angle is arbitrary for forward scattering" and often (i.e. 5/7) generates original analogies.

Phys_2 replied to the follow-up query saying: "I would tend to bring it as far as I need. i.e. If I felt a better understanding was being gained from using it I would carry on with it." In the on-line questionnaire he had said he occasionally (i.e. 3/7) has difficulty getting a mental picture of the physical processes involved in his research because here is, "No tangible evidence for what's going on." To overcome his difficulties he will "try drawing a picture or similar visualisation." He had also said he uses analogy "all the time" in his research, e.g. "Polarisation flipping in lasers describes using potential wells similar to ball on a hill" and often (i.e. 5/7) generates original analogies.

Phys_193 said in the on-line questionnaire that he uses "analogy all the time/7" in his research and also generates original analogies "all the time/7". Recall that **Phys_193**'s example of analogy (shown in table 5.1) compared a parallel plate resonator to a cheese sandwich connected to a stereo. He replied to my follow-up question saying:

> "In my line of research [his PhD was on "Non-linear Behaviour in HTS and MgB2 Superconductors at High Microwave Power"] I've found that an analogy is used mainly as a way of explaining an idea to either non specialists or to explain a new concept to co-workers. We all need something to relate to. As physics is explained using mathematics as a tool, it is difficult to see how you can use analogy to justify an argument rigorously. Analogy could be used in scientific papers to explain new or difficult theories but I think that as you put it analogy is used only as an exploratory tool in the early stages of research." (Phys_193)

Thus, in his line of research analogies fall mainly into set **A,** or possibly set **B**, but not set **C** of the venn diagram shown in section 5.5. The follow-up question prompted considerable self-reflection on the part of **Phys_193**. He added:

> "I hope that the answers are satisfactory. Having thought about your questions I am unsure of the result of the unconscious mind on the formation of ideas. What I mean is sometimes you have an idea about something when you are doing something else which has no connection to what the idea is about. Could the mind not be making analogies to what we are doing unconsciously but we just don't get it? It would be interesting to know your opinion about this."

Phys_193 makes a very interesting point. As discussed in chapters 3 and 8, numerous studies from the history of science suggest that creative insights often come during periods of relaxation, after a scientist has undergone a period of intense intellectual activity. The high-energy physicist and popular science writer, Fritfof Capra (1992) emphasises this point, saying:

> "The rational part of research would, in fact, be useless if it were not complemented by the intuition that gives scientists new insights and makes them creative. These insights tend to come suddenly and, characteristically, not when sitting at a desk working out the equations, but when relaxing, in the bath, during a walk in the woods, on the beach, etc. During these periods of relaxation after concentrated intellectual activity, the intuitive mind seems to take over and can produce the sudden, clarifying insights which give so much joy and delight to scientific research." (Capra, 1992, p.39)

I also pursued this line of questioning (on the use of analogy as scaffolding) with **Phys_128** because he said in the on-line questionnaire that he uses analogy "all the time/7" in his research and very often (i.e. 6/7) generates original analogies. He replied to my follow-up query saying:

> "Analogies are at the heart of my research. I am looking for connections between apparently separate phenomena, such as light in transparent materials like glass or water and light in curved space-time. I try to find out the similarities and, once this is established, I apply the theory developed for one subject in order to understand the other. I feel that this is an extremely fruitful and enjoyable approach which combines mathematical rigor with creativity and imagination. The analogies are not discarded, they are vital and make it into the research papers." [99]

He went on to say that, "... In builders' terms, in an established field the analogy is not the scaffolding, but the foundation." When responding to the on-line questionnaire he said the following example is an analogy he uses in his research:

> "The black hole resembles a space-time river racing towards a water fall, Singularity Falls. Picture a river with fish that have a maximal velocity, say c. If the river flows faster than c the fish are swept away. "

[99] **Phys_128,** is a 37 year old, male, with a German Diploma in Physics; PhD in Theoretical Physics; Habilitation in Theoretical Physics. His current job title is Professor of Theoretical Physics. His research interests include, "artificial black holes, Bose-Einstein condensates, emergent space-time geometries in quantum optics and soft condensed-matter Physics." In the on-line questionnaire, he said he very often (i.e. 6/7) has difficulty getting a mental picture of the Physical processes involved in his research. He said, "If I have got the mental picture the research is mostly done. So getting the picture is as difficult as doing research. Here the difficulty depends on the choice of topic... Quantum phenomena are hard to comprehend."

I assumed **Phys_128** was using the S*ingularity Falls* analogy primarily to communicate science to intermediates and novices. That is, it would fall between sets **A** and **B** in the venn diagram of figure 5.3. Recall that set **A** contains verbal or physical or pictorial analogies with low level systematicity, used by physicists in the playful exploration of ideas and when communicating with novices. Set **B** contains physical or pictorial analogies with medium level systematicity used to provide experts, intermediates and novices with insights in the conceptualisation and communication of physics. Set **C** on the other hand, contains more abstract, mathematical analogies, with high level systematicity and tend to be used in a structured way as tools of exploration in research and when explaining concepts to peers. However, it was possible that **Phys_128** also used it in private conceptualisation or when communicating with peers. Thus, in the same follow-up e-mail, I asked him: *"In what contexts have you used the Singularity Falls analogy? E.g. private conceptualisation, communicating with peers, research students, the general public?"* Somewhat to my surprise he replied, "In all the cases you mentioned, even in the introduction of original research papers and in grant proposals. It is a superb analogy." It is unusual for an analogy to span all three sets, **A, B** and **C**, so, what makes the *singularity falls* analogy a "superb analogy", useful in so many different contexts? Like many analogies which feature in set **A**, it draws on everyday concepts, is easily expressed (verbally and graphically) and is memorable. However, analogies of this kind are not commonly used in scientific papers. I believe that an important factor may be its esteemed origins. It is attributed to William G. Unruh, one of the pioneers of black hole quantum mechanics. The analogy was also used by Leonard Susskind (one of the pioneers of String Theory) in a **Scientific American** article in 1997. (See figure 5.4 on next page). I discuss this hypothesis in section 5.6.1 below, where I look at the use of analogous visualisations in popular science articles and scientific journal articles.

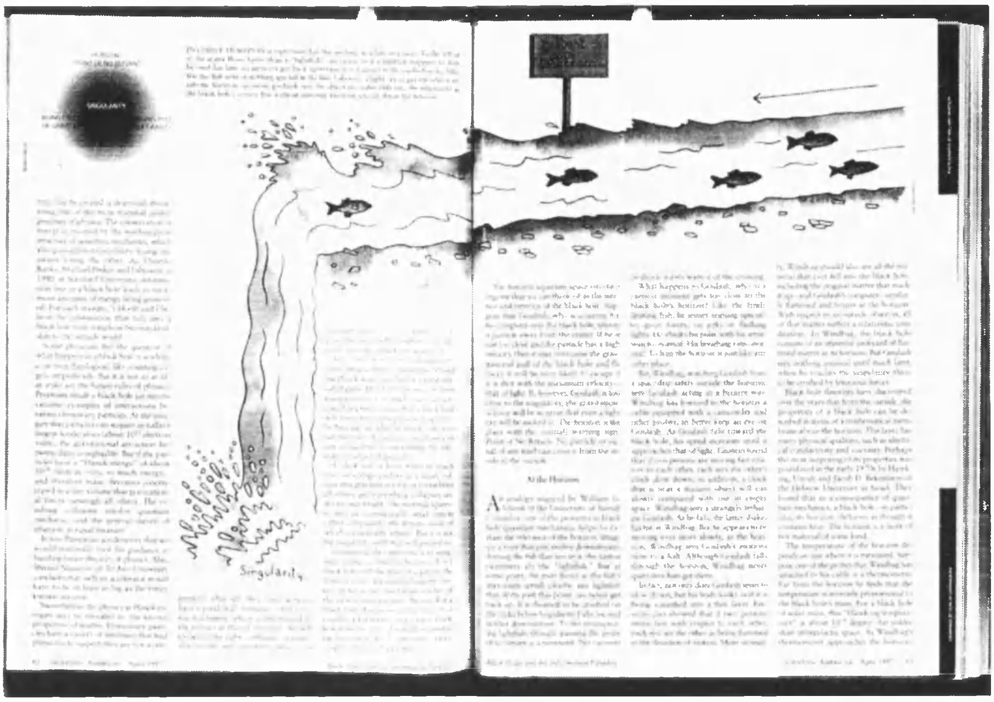


Figure 5.4: The sketch that accompanied Leonard Susskind's article on "Black Holes and the Information Paradox." (Scientific American, April 1997, pp. 40-43)

5.6.1 The use of analogous visualisations in popular science articles and scientific journal articles.

In 2003, Carlo Rovelli wrote an article on quantum gravity in **Physics World,** entitled, "Loop Quantum Gravity." (Rovelli, 2003, pp. 37-41). Rovelli's article contains five images pertaining to his topic of discussion. I was interested to uncover at what point in the conceptualisation and communication process such visualisations tend to be employed and at whose suggestions (i.e. the magazine editor or paper author). Would physicists use similar visualizations in their journal articles if they thought it was acceptable? I asked **Physics World** editor, Peter Rodgers about this in an email (11-11-2003).

Responding to my query about the differences between popular science magazines' use of images and journal articles' use of images, Rodgers said that in his experience, "research papers (rightly) focus on schematics of the experiment etc. and graphs/plots with the actual data. The problem with strings is that there isn't really any data and no one knows how to visualizse 10-dimensions!" Rodgers told me that the lack of images at their disposal (pertaining to e.g. string theory and loop quantum gravity), "presents real problems for a magazine like PW where we try to make articles LOOK interesting/appealing and also try to make them understandable by non-expert (albeit a non-expert with a physics degree)." He said that, "[m]ost pop articles on strings I have seen either resorted to the standard boring diagram (e.g. p.30/33) or completely invented computer-generated landscapes (as does the Brian Greene programme [e.g. last episode shown on channel 4, Sunday 16th Nov 2003])." He said that in general, in **Physics World,** they "choose images that look nice and help the reader understand what it gong on."

Rodgers said that the images on pages 37, 38, 39 and 40 of Rovelli's article were "all sent by the author." He said the image on page 41 was "suggested" by the staff at **Physics World** because they "had used this image in an article on quantum gravity before." One might ask: if Rovelli sent the images to **Physics World,** are they something he uses in his scientific publications, or only in his popular science publications? A review of thirty or so of Rovelli's recent scientific publications shows that many contain mathematical and geometrical representations but only one conference paper contains an image of the kind used in physics world. This was in a paper entitled: "Notes for a brief history of quantum gravity." (Rovelli, 2000, web ref). Rovelli says in the introduction of this paper:

> "When John Stachel asked me to prepare a brief history of the research in quantum gravity for the 9th Marcel Grossmann Meeting, I trembled at the size of the task, worried of repeating only information already known to everybody, and feared to displease my colleagues. John managed to convince me to try anyway, and here is the result." (Rovelli, 2000, web ref., p.1)

As we will see in chapter 6, communicating physics to an audience composed of people of differing levels of expertise is daunting to most physicists. Speakers worry that an overly complex talk will confuse those with limited expertise in physics, but an overly simplistic talk will patronise experts in the audience. As I discuss in section 6.6 Kroemer's approach in his Nobel laureate address (cf. Kroemer, 2000, web ref.) is to begin by using physical and pictorial analogies to present a simple picture, then to build up to more technical explanations. In this way Kroemer is able to satisfy most of the audience: introducing the subject to novices and reminding experts of the achievements made.

During his conference talk, Rovelli (2000, web ref., p.17) provides a basic overview of the history of quantum gravity. He notes, for example, that that the notion of a weave, "is evidence of a discrete structure of spacetime emerging from loop quantum gravity" and adds that "the first example of a weave which is considered is a 3d mesh of intertwined rings." In Rovelli's (2003) **Physics World** article, this notion of weaving space was illustrated by the image on page 37 of the magazine (see figure 5.5 on the next page)

However, at this conference of experts and intermediates Rovelli (2000, web ref.) does not present the same image. Instead he entertains his audience with a playful version which extends the analogy far beyond the domain of quantum gravity to the domain of popular culture, thereby highlighting the limitations of such analogies, a common techniques used when communicating with experts. He quips, "not surprising, the intuition was already in Wheeler! See Figure 1, taken from Misner, Thorne and Wheeler (1973)." (Rovelli, 2003, p.17). See figure 5.6. Thus, like the *Singularity Falls* analogy, the 'weave' analogy can be traced back to an eminent theoretical physicist – in this case John Wheeler, who also introduced the idea of 'spacetime foam' in 1963 and, among other things, coined the term 'black hole' in 1967. Thus, there is some evidence to indicate that an analogy is more likely to span sets **A, B** and **C** (i.e. be used with experts a well as novices in formal and informal settings) if attributed to an eminent physicist, renowned for generating useful visualizations in private conceptualisation and expert-novice communication. This point will be picked up in chapter 6.

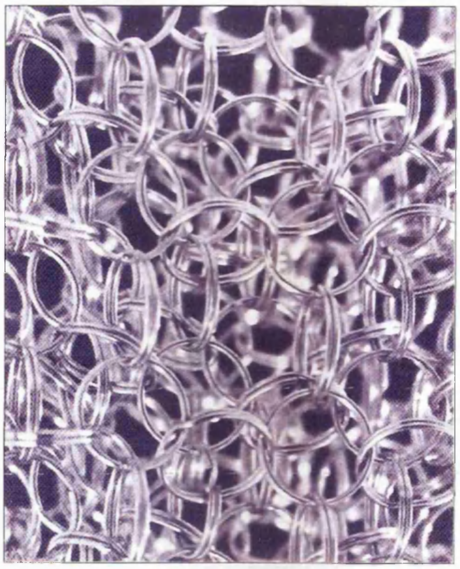


Figure 5.5: Image illustrating the notion of weave, used in Rovelli's (2003) Physics World article. This was one of four images which Rovelli sent Physics World.

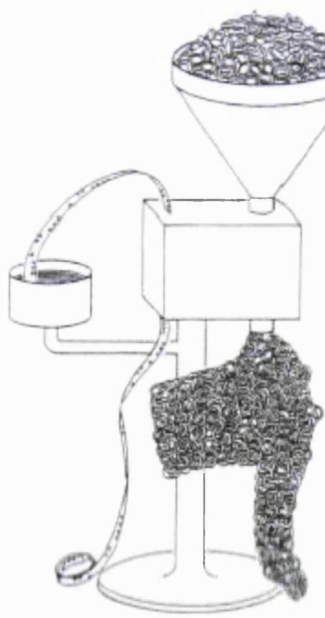
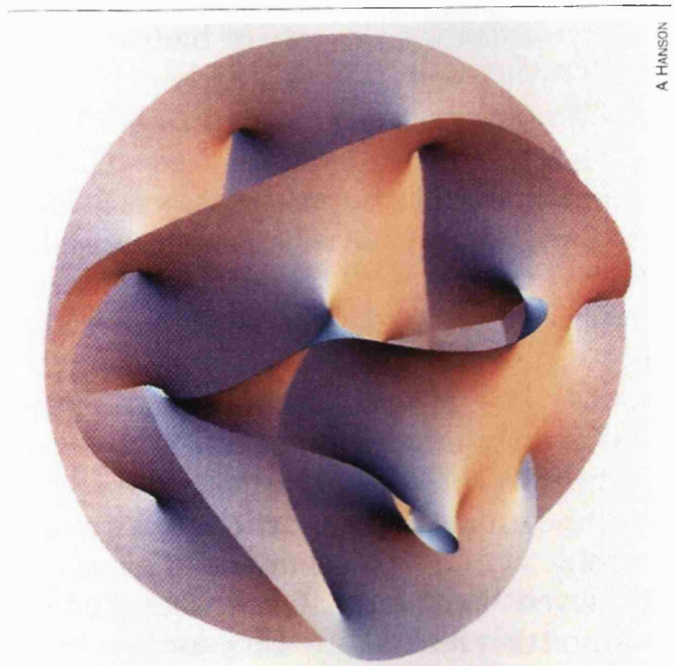


Figure 5.6: The Notion of 'weave' appeared in the richly illustrated book, "Gravitation" by eminent theoretical physicists Misner, Thorne and Wheeler in 1973. It also featured in a conference paper by Rovelli (2000) in which he provided a brief history of quantum gravity.

Like Rovelli, Leonard Susskind also wrote an article in the same issue of **Physics World** entitled "Superstrings" (Susskind, 2003). This article also contained five images relating to string theory. However, unlike Rovelli, it seems that Susskind only submitted sketches for fig1 (p.30), fig3 (p.33) and fig4 (p.34) once he was pressed. Rodgers told me:

> "We found the image on page 29 ourselves (from Andrew Hanson [100] at Indiana). We knew about Hanson because we had used a similar image of Calabi-Yau manifold produced by him before. We sort of came up with the image on page 32 ourselves (based on diagrams we has seen elsewhere)."

Opposite is a scan of Hanson's creation, taken from the **Physics World** publication. The computer generated image also appeared in Brian Greene's books *The Elegant Universe* (1999), and *The Fabric of the Cosmos* (2004), and in Callender & Huggins (2001), *Physics Meets Philosophy at the Planck Scale.* As **Physics World** editor, Peter Rodgers said, there is a lack of images pertaining to string theory. Thus, when colourful visualisations, based on quite well-established mathematical theory, are generated (by people like Hanson) they are used repeatedly in popular science publications.



String space – superstring theory lives in 10 dimensions, which means that six of the dimensions have to be "compactified" in order to explain why we can only perceive four. The best way to do this is to use a complicated 6D geometry called a Calabi–Yau manifold, in which all the intrinsic properties of elementary particles are hidden.

Figure 5.7: Hanson's image of string space included by Physics World staff to make the article look interesting/appealing and understandable by non-expert, with a degree in physics.

[100] [Hanson is currently Professor of Computer Science at Indiana University. He has a PhD in theoretical physics. His most recent research focuses on *Mathematical Visualization, Virtual Reality, and Astronomy.* See Hanson's website for numerous images and animations: http://www.cs.indiana.edu/~hanson/ (Last accessed 01-03-2006)]

Responding to my query about the differences between the use of analogous visualisations in popular science magazines and scientific journal papers, Rodgers said that:

> "Illustrating abstract/highly theoretical topics like strings is always difficult. The original research papers themselves rarely contain illustrations. I don't know about talks etc. at conferences – however, 'overheads' are available for most conferences in this field ... "

Following Rodgers' suggestions, I looked at the 'overheads' and audio recordings for the **Strings 2003 Conference.** Susskind did not attend the conference so the over-heads and live video recording of another eminent theoretical physicist, Ed Witten, were analysed. [101] At one point in his talk to an audience of experts, Witten uses a trampoline analogy when talking about the warping of spacetime according to general relativity, but is cautious to identify the limitations of the analogy. Regarding electron spin, he says, "I can draw the picture, but the picture is wrong" because it requires matrix description. Near the end of his talk he presents an artist's conception of something but remarks that he doesn't really like artists' conceptions of physics. Perhaps Susskind only supplied **Physics World** with sketches when he was pressed because he shares a similar view to Witten regarding artists' conceptions of physics? The concrete nature of analogous visualisations can be misleading if taken them too literally. As we saw in section 4.6.3, many questionnaire respondents noted that the immediacy of computer simulations can be powerful but misleading. Similarly in section 5.3.4 we saw that many questionnaire respondents said that they avoid using analogies because they believe that they can be overly simplistic and misleading if taken too far. The latter issue is discussed further in chapter 6.

5.7 Are certain branches of physics more open to analogical reasoning than others?

Thus we can see that for some physicists, like **Phys_128** "The analogies are not discarded, they are vital and make it into the research papers." For others, like **Phys_193**, "Analogy could be used in scientific papers to explain new or difficult theories but I think that as you put it analogy is used only as an exploratory tool in the early stages of research." While others, like **Phys_150**, [102] "have used analogy predominantly in informal settings, as a means of increasing enlightenment." **Phys_150** added, "I am not aware of using analogy in a journal publication, but believe that a cautious use is accepted by the journals of interest

[101] In section 6.3 I present some of Ed Witten's 'overheads' and comment on his use of freehand diagrams and style of address.

[102] **Phys_150** is a 56 year-old, male, with a BSc in Physics; PhD in High Energy Physics and post-doctoral experience in High Energy Physics. He is currently employed as a Research Assistant, interested in, "Detectors for High Energy Physics and Astronomy."

to me."[103] **Phys_128**'s experiences of analogical use in scientific papers appear to differ from **Phys_150**'s. This was not particularly surprising. My pilot study work (Muldoon, 2002) showed that the term "analogy" featured more frequently in the titles and abstracts of journals in some branches of physics (e.g. cosmology) than others.

Basic quantitative analysis was carried out on the on-line questionnaire data to see if there were any obvious relationships between respondents' use of analogy and the 12 Institute of Physics groups with which they associated themselves.

Q1a. With which of the following groups would you associate yourself?	**Number of respondents who associated themselves with this group**	**Q3. Do you ever use analogies in your research?**						
		1/ Never	**2**	**3**	**4**	**5**	**6**	**7/ All the time**
Applied Optics	*43*	**11.6%**	9.3%	9.3%	9.3%	25.6%	9.3%	25.6%
Chemical Physics	*28*	**0.0%**	7.1%	10.7%	14.3%	28.6%	14.3%	25.0%
Computational Physics	*55*	**0.0%**	12.7%	9.1%	3. 6%	38.2%	10.9%	25.5%
Surface Science & Technology	*20*	**0.0%**	0.0%	15.0%	15.0%	30.0%	15.0%	25.0%
Nuclear Physics	*18*	**11.1%**	11.1%	0.0%	16.7%	22.2%	22.2%	16.7%
Plasma Physics	*24*	4.2%	8.3%	8.3%	8.3%	37.5%	16.7%	16.7%
Condensed Matter & Material Physics	*68*	4.4%	4.4%	13.2%	13.2%	27.9%	13.2%	23.5%
High Energy & Particle Physics	*37*	2.7%	18.9%	13.5%	5.4%	24.3%	10.8%	24.3%
Mathematical & Theoretical Physics	*65*	**0.0%**	10.8%	12.3%	4.6%	27.7%	7.7%	**36.9%**
Spectroscopy	*37*	2.7%	10.8%	5.4%	10.8%	29.7%	16.2%	24.3%
Quantum Electronics & Photonics	*40*	**0.0%**	10.0%	10.0%	17.5%	25.0%	12.5%	25.0%
Astrophysics	*60*	**11.7%**	13.3%	8.3%	6.7%	33.3%	13.3%	13.3%

Table 5.3: Shows the degree to which respondents, who associate themselves with certain research groups, use analogy in their research.

Although there does not appear to be any clear relationship on the positive end of the scale, there does appear to be one on the negative end of the scale. No respondent who associated

[103] In Q1 of the questionnaire **Phys_150** associated himself with 2 of the 12 Institute of Physics groups: "Computational Physics" and "High Energy Particle Physics" so the journals "of interest" to him are likely to lie in these areas.

themselves with “Chemical Physics”, “Computational Physics”, “Surface Science and Technology” or “Quantum Electronics and Photonics” said they **“never/1”** used analogy in their research. This is in contrast with over 11% of respondents who associated themselves with “Applied Optics”, “Nuclear Physics”, or “Astrophysics” who said they **“never/1”** use analogy in their research. These respondents may not be representative of researchers involved in those fields so I will not attempt to draw any generalisations from these results.

However, I will suggest that the data could be used to support the view that the respondents who said they never used analogy in their research held a narrower interpretation of the term “analogy” which excluded mathematical analogies. The fact that the largest proportion of “use analogy all the time in research” responses came from respondents who associated themselves with “Mathematical and Theoretical Physics” gives credence to this hypothesis.

The question of whether analogy is more common in some branches of physics than others was investigated in follow-up e-mail exchanges with a select sample of respondents, most of whom were enthusiasts for analogy. The following question was addressed to **Phys_27:**

> *“You indicated that you frequently use analogy in your research and often coin original analogies...Is analogical use common in your research area? Is it considered an acceptable means of problem solving?”*

Phys_27 replied saying:

> “My research area is mostly in Carbon nanotubes, with a lot of work in their growth and production. Many analogies are used to describe new growth forms such as: "nano-trees", "bamboo structure" "nano-onions" etc. These analogies not only are a succinct way of describing a new structure, but are also useful as a way of marketing your research to other scientists in the titles of your papers or posters. People are more likely want to know more about your research (ie read your paper or look at your poster) if they can easily identify with some concept in your title or abstract, the more commonly understood the concept the more people will be likely to read your paper.”

Phys_27 seems to be underscoring an issue mentioned in the previous chapter; that promoting one’s research is vital if one is to receive the support of peers, funding bodies and the general public. It is a question of making good science look good and sound interesting.

In an effort to understand whether certain branches of physics seem more open to analogical reasoning than others, the following question was posed in follow-up e-mails to **Phys_2, Phys_19, Phys_128, Phys_193 and Phys_202:**

> *Q. The findings of my research suggest that certain branches of physics seem more open to analogical reasoning than others. Do you have any experience of this? For example, have you encountered different ways of 'doing' and 'presenting' physics while carrying out interdisciplinary research or publishing papers in journals from different fields?*

Several responses highlighted the fact that analogies can take different forms. Focusing on the physical component of analogies, **Phys_2**, a PhD student, whose research interests include: "Vertical cavity devices, communications, high output devices" said: "Not as such, though I would suggest that practical subjects can be more readily interpreted via analogies."

In contrast, **Phys_19** focused on the abstract, mathematical component of analogies, saying:

> "... one must remember that I am a Theoretical Physicist who would consider himself to be an expert in applied mathematics. Thus many analogies are not merely 'physical' but mathematical: eg we might solve a particular equation in, say, mathematical biology, the way we solved Ricatti nonlinear equations in above immediate threshold electron-atom collisions."

Thus, it is not unreasonable to assume that theoretical physicists in the sample were probably interpreting the term analogy in a more abstract, less physical way than the experimental physicists, as I suggested above.

Phys_202, a lecturer in geophysics, was pensive on the question of whether certain branches of physics seem more open to analogy than others. It was not something he had remarked upon within the discipline of physics, but he did notice a contrast between the physical sciences and the social sciences, from his experiences outside of physics e.g. dealing with archaeologists and geologists through his work as a geophysicist. [104]

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[104] "Hmmm. Haven't noticed or thought much about this. Certainly in disciplines outside the physical sciences, analogy seems to be used less, but that's more from my own experience. The social scientists (e.g. archaeologists) seem to try to avoid analogy because they do not want to prejudge their findings, whereas we physical scientists are much more open to it as a way of visualizing our results and findings. Certainly geologists use analogy frequently as a way of connecting similar features and processes." (Phys_202)

Phys_128, who gave the example of the *Singularity Falls* analogy and said that his analogies "are not discarded, they are vital and make it into the research papers," felt that "interdisciplinary research truly based on analogies is quite rare. Unless a subfield with such profile is established, it is also not easy to publish, in particular when a paper demands a high level of understanding in several areas." He said he new of, "a case where a truly outstanding sophisticated paper was rejected time after time until it found a home in a journal." **Phys_128** gave an example from condensed matter physics, where an analogy accounts for 10-20% of the current theoretical research in the area. It is relevant I think to note **Phys_128's** comment that the analogy has come to be "taken for granted". Like a building's foundations, it provides structural support, but is often over-looked.[105] (See section 6. 7 for further discussion in this issue).

5.7.1 Is there a relationship between the number of groups with which respondents associate themselves and the extent to which they use analogy in their research?

Related to the issue of interdisciplinary work and the use of analogy, the on-line questionnaire data suggested a relationship between the number of IoP groups with which physicists associated themselves, and the extent to which they used analogy. Respondents who associated themselves with many groups were more likely to be enthusiasts for using analogy in their research. From figure 5.8 we can see that almost 70% of those who said they *"never/1"* use analogy associated themselves with just one of the 12 IoP groups. In contrast, respondents who associated themselves with 7 or 8 of the 12 IoP groups were clustered on the positive end of the 7-point scale. As we will see in chapters 7 and 8, Dr. Lawson attributed his frequent use of analogy to the fact that he had a wider field of view (with experience in 5 sub-fields of physics) and therefore noticed many analogies.

Again, on the issue of interdisciplinary work, of the 60 respondents who associated themselves with "Astrophysics", 35% associated themselves with no other group. This is shown in appendix 5, table A5.1. By comparison, of the 43 respondents who associated themselves with "Applied Optics" only 9.1% associated themselves with no other group. This suggests that "astrophysicists" are a distinct sub-culture.

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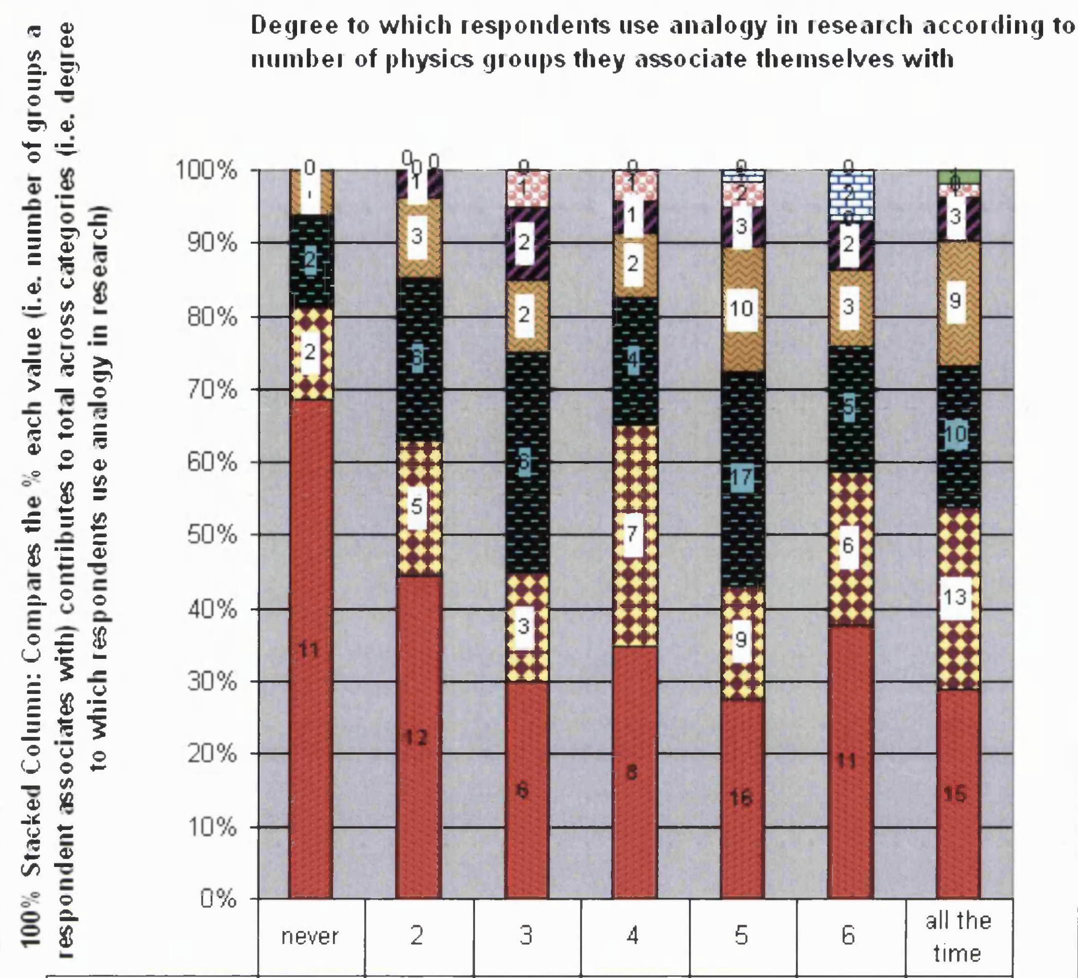
[105] "An example of an established field is the realization of the Hubbard model in condensed-matter physics using atomic Bose condensates in optical lattices. Here a simple analogy between electrons in crystals and atoms in standing light waves caters for, say, 10-20% of the current theoretical research in condensed-matter physics. The pioneering work was to discover this analogy and to demonstrate it in experiments, the rest is follow-up and less original where the analogy is taken for granted. In builders' terms, in an established field the analogy is not the scaffolding, but the foundation. Another famous case is the analogy between polymers and magnetic chains due to Pierre-Gilles de Gennes, Nobel Prize 1991." (Phys_128)



	never	2	3	4	5	6	all the time
assoc 8 groups	0	0	0	0	0	0	1
assoc 7 groups	0	0	0	0	1	2	0
assoc 6 groups	0	0	1	1	2	0	1
assoc 5 groups	0	1	2	1	3	2	3
assoc 4 groups	1	3	2	2	10	3	9
assoc 3 groups	2	6	6	4	17	5	10
accoc 2 groups	2	5	3	7	9	6	13
assoc 1 group	11	12	6	8	16	11	15

The 8 rows above contain the numbers of respondents who made these selections regarding the degree to which they use analogy in their research.

Figure 5.8: Relationship between number of groups with which respondents' associate themselves and the degree to which they use analogy in their research.

Phys_128 mentioned that scientific journals sometimes reject outstanding research because it does not fit their particular profile. As you will see in section 5.8, Prof. Berry's experiences suggest that there are particular journals within physics that are less accepting of the use of analogy and other forms of creative language.

5.8 Censorship of Creative Language: A diabolical point for Physical Review Letters?

A particularly interesting and novel result to emerge from my research is the apparent censorship of creative language by some American Institute of Physics journals. This is related to the issue of reasoning by analogy because it is a consequence of journals requiring physicists to retrospectively present their work in a logical, deductive manner, editing out the creative insights and playful associations which led them to their discoveries. The biologist Evelyn-Fox Keller remarks upon this "erasure" and "representational logic" saying:

> "The man-made (or more accurately, men-made) nature of scientific knowledge cannot be represented in the texts of science, for precisely what has been constructed is the illusion that this knowledge is not made by men -- not crafted, articulated, or constructed, but discovered, in a word, simply true." (Fox-Keller, 1996, p.420)

I do not adhere to social constructivism or scientific relativism but I do believe that the "erasure" and "representational logic" inherent in scientific papers leave little room for the creative use of language with a view to making the topic engaging. Prof. Berry told me that: "some of the most prestigious [American Journals], according to the fashions of the time, are too interventionist and they don't allow the creative use of language. There are several terms that I've invented which they have censored … " I asked, "what terms?" and Prof. Berry replied: "Oh ***diabolical point*** - - In fact my lecture in Ireland [a previous topic of conversation for us] was: ***'Hamilton's Diabolical Point.'"***

Prof. Berry explained this term, saying:

> "Certain mathematical constructions involve a double cone. A double cone is a diabolo. It's also the organising centre of degenerate behaviour. So it seems good to call it ***diabolical.*** It's a term I introduced **DECADES** ago in proceedings of the Royal Society with proper reference to the Oxford Dictionary and all this. And people use it! It's caught on in nuclear physics – {inaudible} - based on a paper I wrote. But **Physical Review Letters** don't allow it." (Prof. Berry 05-07-2005)

Diabolical point is not the only one of Berry's terms censored by Physical Review Letters, however. Another term coined by Prof. Berry "Quantum Chaology" has also been censored. [106] Although the term "diabolical point" has caught on amongst Prof. Berry's

[106] Prof. Berry continued: "Another one is *Quantum Chaos*. A commonly used expression, but strictly speaking there isn't any. At the beginning of the subject there was a lot of confusion – what are we studying? – there's no chaos in quantum Physics in the technical sense. And I had to say, actually I'm not studying chaos in quantum Physics, I'm studying the reflections of chaos in classical Physics. So it's *Quantum Chaology*, that I use. But they don't allow those either. Again the first time, I think my Bakerian lecture at the Royal Society in 1986 was called *Quantum Chaology*. It began by quoting from the Oxford English Dictionary, saying *Chaology* was an old term used in Theology which meant 'that which existed before the

peers, and been used in the titles of his public lectures to pique listeners' curiosity and make the topic more memorable (a key component of good science communication), the rules and conventions of Physical Review Letters prevent him from using the same creative language when communicating with his peers. One could argue that, unlike popular science magazines or books, the purpose of a research paper is to establish some facts or models, not to explain how they were thought up; that a playful term adds nothing to the establishment of scientific facts and merely connotes personal quirkiness. However, I believe that the attempt to maintain some kind of conceptual and linguistic purity is misguided.

The key point is that such terms are not being used in a justificatory capacity but in something akin to a marketing capacity. As we saw in section 5.7, the experiences of **Phy_27** suggest that analogies are, among other things, "useful as a way of marketing your research to other scientists in the titles of your papers or posters." I would argue that an intelligent and creative use of language should have an important function in the scientific enterprise. The number of scientific publications has increased exponentially in the past decade as the scientific community grows and lives in the shadow of a "publish or perish" regime. Scientists are often portrayed in the media as cold, detached, logical, objective, semi-human beings who prefer their laboratory equipment or equation-covered whiteboards, to things from popular culture. Of course this stereotype is nonsense. Scientists, just like everyone else, are more likely to read something if it catches their attention or arouses their curiosity. An interesting title or abstract is the best way of 'hooking' the prospective reader or listener. Examples of catchy titles from public talks are Prof. Berry's public lecture, ***"Making Light of Mathematics"***, [107] and Prof. Paul Coleman's inaugural lecture, ***"Probing Matter with Anti-Matter: A Career in Self-Annihilation."*** [108] I believe the same basic principle could hold when publishing scientific papers. Once the target audience has been 'hooked' they will proceed to read and absorb the detailed content of the paper. The content will then be stored in memory and associated with the catchy title, thereby facilitating subsequent recall. This strategy is the cornerstone of marketing. I believe such marketing techniques have a place in all areas of the scientific enterprise, particularly if used in an intelligent, thoughtful way. In fact, Prof. Berry touches on this point when he says that his "complaint to [Physical Review Letters] is that this is a

creation.' It's not used anymore. It's a minor branch of theology. Even when the Oxford English Dictionary was first written in 1890 or so it was even then obsolete, so we published it and defined it carefully. But Physical Review Letters didn't like it." (Berry, during our interview of 05-07-2005)

[107] delivered on 30th April 2003, to an audience of about 100 people at the Hewlett Packard Labs in Bristol, UK. Also related by video-link to the HP Labs in Palo Alto, California and Cambridge, Massachusetts.

[108] delivered on 1st May, 2003, to an audience of about 100 people, at the University of Bath, UK.

form of censorship… when other people use [the term diabolical point], it means it satisfies a free market test." He concludes by saying: "I can't be bothered with the hassle, so I don't publish in Physical Review Letters." I believe that scientific journals should be more open to the communication techniques employed by creative scientists, like Prof Berry, who obviously care a great deal about language and know how to use it to its fullest potential to educate, entertain and inform physics experts, intermediates and novices. I hope that my research will go some way towards promoting this view.

5.9 Conclusions

As mentioned in chapter 2, the on-line questionnaire was intended to be a form of reconnaissance: to provide a map of the territory and highlight key issues for exploration during subsequent follow-up studies. In this capacity it was extremely successful, producing a mountain of information which continues to be mined. It also reached a large cross section of the physics community, providing numerous volunteers for these subsequent studies. However, as Dunbar's research has shown, analogy is often used as scaffolding, discarded and forgotten after it has served as a bridge when building new explanations and models, (cf. Dunbar 2001). Thus, physicists' **self-rated use** of analogy may not be representative of their **actual** use of analogy, so in-depth studies, which do not rely on self-rated responses, may prove useful.

Nevertheless, it is clear from an analysis of the empirical data gathered via the on-line questionnaire, follow-up e-mails and semi-structured interviews that there are numerous and complex factors at play in physicists' use of analogy in scientific research. Firstly, there is no unanimous definition of what constitutes analogy. Some physicists appear to only associate analogy with textbook physics and consequently regard it as overly simplistic and misleading. Other respondents hold a broad definition of analogy that includes complex mathematical analogies and simple visual analogies. For these physicists, complex analogies are used almost exclusively in formal settings (private conceptualisation & communication with peers), while the simple analogies are used in informal settings (private conceptualisation and communication with peers, intermediates and novices).

Taking this into account, use of analogy in research was widespread among the physicists who responded to the on-line questionnaire. In section 5.2 I showed that 52 respondents (23.1% of the sample) said they use analogy "all the time" in their research. This is over three times as many as those that claimed to "never" use analogy in research. The reasons given by respondents for not using analogy in research fell into four main categories: (i) they didn't need to use analogy because their work was already easy to visualise, (ii) analogies were too difficult to formulate because their subject matter was highly abstract, (iii) analogies only seem appropriate for non-specialist audiences, (iv) analogies are overly simplistic and can be misleading.

In section 5.4 I showed that when commenting on the degree to which they use analogy in research 61.8% of respondents selected between **5** and **7** on the 7-point scale which runs from "never/1" to "all the time/7". However, when commenting on the degree to which they generate original analogies, 60.8% selected between 1 and **3** on the 7-point scale. This indicates that, a majority of respondents are aware that they mostly use an existing stockpile of tried and tested analogies, rather than generating original analogies. However, as shown in table 5.1, several respondents provided examples of original analogies which they have found useful when conceptualising and communicating physics. From this we can see that playful analogies, drawn from everyday experience, do have a place in the scientific enterprise, although they rarely make it into scientific publications. I suggest that an analogy is more likely to span sets A, B and C (i.e. be used with experts and novices) if it is attributed to an eminent physicist with a flair for generating useful visualizations in private conceptualisation and communication.

The 147 examples of analogies supplied by respondents fell into three broad categories:

(i) verbal, physical or pictorial analogies used to play with ideas in private conceptualisation; and to make physics accessible, memorable and fun when communication with novices in all settings and with colleagues in informal settings.

(ii) physical and pictorial analogies used as heuristics in problem solving, to provide physical and pictorial insights;

(iii) mathematical analogies used as structured tools of exploration, in theory building and when communicating with peers who are experts in physics;

Mathematical analogies and physical & pictorial analogies are frequently used by respondents in their research. Although they rarely appear in journal papers, original, playful analogies also have their place in scientific research – to conceptualise and communicate novel ideas and enlist support. This was a surprising finding and one which could have useful applications in the area of science education. For example if playful analogies could be used in a structured, integrated way they may help students to conceptualise physics without encouraging a naïve interpretation of the analogy. The use of analogy in science communication is discussed further in the next chapter.

Chapter 6
Key factors that influence physicists' use of analogy when communicating with audiences of different backgrounds

Truth & Uncertainty

(By Ciara Aisling Muldoon)

Sleepwalkers in a cosmic maze,
Searching for a golden thread,
Some stumble, fumble, in a daze,
Following their dreams instead.

With Mathematics as their guide,
Some journey through shadowlands,
Where Nature's timid secrets hide,
Phantoms slipping through their hands.

Those shadows danced in Plato's cave
Two millennia ago,
Now as a particle and wave
They passionately tango.

The vibrant music of The Spheres
Orchestrates the melody,
From Timeless Beauty, Truth appears
And with her, Uncertainty.

6.0 Overview:

This chapter explores the key factors that influence physicists' use of analogy when communicating with audiences of different backgrounds. As in chapters 3, 4 and 5, the data is derived from the responses of 225 physicists to my on-line questionnaire on visualization, analogy and computer simulations; follow-up e-mail responses with a select sample of 13 questionnaire respondents; observation of Professor Paul Coleman's inaugural lecture and our subsequent e-mail exchanges; and my semi-structured interview with Professor Sir Michael Berry. I will address the following research questions in this chapter:

- To what extent do these physicists use analogy when communicating with different audiences?
- Can analogical reasoning provide insights when conceptualising and communicating physics?
- To what extent do (a) physics expertise of audience; (b) tone of discussion; (c) nationality of audience affect physicists' use of analogy?
- What forms of analogy do they use in different contexts?
- What are the characteristics of good analogies?

My findings will show that physicists who are enthusiasts for analogy in their own research tend to tailor their analogies when communicating with different audiences. In particular, the analogies they employ increase in complexity as the audience's level of **expertise** increases. With experts, they use complex analogies drawn from within the domain of science. These analogies have an underlying mathematical structure, but sometimes lack pictorial or physical components. In contrast, with novices, they use simple analogies drawn from everyday experiential knowledge. These analogies are made accessible to novices by their pictorial and physical components. Essentially, the aim is make physics accessible by finding common ground that one can build upon. Experts have everyday experiential knowledge plus specialised physics knowledge. Therefore, when experts communicate with one another they have a larger common ground upon which to build. When writing scientific papers, they build upon the most solid ground, i.e. mathematical foundations. When they are playfully exploring new ideas, or marketing their research to peers, funding bodies or the general public, they build upon something more visually engaging and memorable.

6.1 "When it comes to atoms, language can only be used as in poetry."

As discussed in section 0.7, although conventionally thought of as polar opposites, physicists and poets are similar in at least one respect: both are creative in devising symbol systems with which to represent their subject matter. As Neils Bohr once remarked, the atomic physicist and the poet are engaged in a similar enterprise, "not nearly so concerned with describing facts as with creating images," because, "[w]hen it comes to atoms, language can only be used as in poetry" (Bohr, quoted in Bronowski, 1973, p.340). Werner Heisenberg,[109] also pointed out the difficulties of describing quantum physics in words in 1963. He said: "we have at first no single guide for correlating the mathematical symbols with concepts of ordinary language; and the only thing we know from the start is the fact that our common concepts cannot be applied to the structure of the atom." (Heisenberg, 1963, pp. 178-179). Many contemporary quantum physicists still face similar problems described by Heisenberg (1963) when trying to communicate their ideas to a non-specialist audience. The high-energy physicist and best selling popular science author, Fritjof Capra (1992, p.38) tells us that eventually physicists will want to talk about their results to non-physicists and "will therefore have to express them in plain language. This means they will have to formulate a model in ordinary language which interprets their mathematical scheme." According to Capra, "even for the physicists themselves, the formulation of such a verbal model...will be a criterion of the understanding they have reached." So what techniques do physicists employ in order to communicate such counter-intuitive and abstract things as quantum physics? Do they employ analogy, and if so, what kinds?

6.2 Bakhtin's Speech Genres, Utterances and Addressivity

Literary theory offers some useful terminology and theoretical tools with which to analyse the science communication facet of this project. The key terms of interest to us are 'utterances' and 'addressivity'. According to Bakhtin, words and sentences are impersonal; they belong to nobody and are addressed to nobody. In contrast, an utterance has both an author and someone to whom it is directed. This is its 'addressivity' (Bakhtin, 1986, p.95). Bakhtin, says that when speaking he always takes into account the "apperceptive background of the addressee's perception of my speech". For instance, "the extent to which he is familiar with the situation, whether he has special knowledge of the given cultural area of communication, his views and convictions, his prejudices (from my

[109] who laid the groundwork for today's quantum physicists and gave his name to The Uncertainty Principle which says that one cannot precisely determine the exact position and momentum of a particle at the same time. Only the probability of its location at a certain time can be predicted.

viewpoint), his sympathies and antipathies – because all this will determine his active response and understanding of my utterance." (Bakhtin, 1986, p.96). According to Bakhtin, in sum, "it all comes down to the scope of his specialised knowledge." (ibid.) In chapters 7 & 8 I show that Dr. Lawson explicitly constructed his utterances in the knowledge that e.g. theoreticians, who originated from countries lacking a tradition of experimental science, tended to be more mathematically inclined.

Thus, the key to good communication is to place yourself in the minds of your audience: to estimate their expertise, their level of English proficiency, their cultural background, their interests etc. When using analogies as explanatory devices, it is important to realise, (as some on-line questionnaire respondents did), that an audience from Hungary may not be familiar with the landscape of the Arizona desert; an American audience may know nothing about cricket; and an Irish audience may have no kinaesthetic awareness of ice-skating. Obviously an audience is not homogeneous: it is composed of individuals with different backgrounds. Thus, tailoring one's talk to one's audience can be a difficult task. One risks boring the experts if a talk is overly simplistic and boring the novices if a talk is overly complex. Recall that in section 5.5 I categorised the 147 examples of analogies employed by respondents in their research according to their form, function and context of use. I found that the largest proportion fell within set **B.** These analogies had greatest 'addressivity' because they drew on an intermediate range of concepts, descriptions and processes.

Some questionnaire respondents' seemed to gauge the background knowledge of their audience in a probabilistic manner. For example, when asked to what extent the physics expertise of his target audience influenced his use of analogy, **Phys_25**, (a 40 year old lecturer), said he would ask himself: "Are they undergraduates or fellow researchers?" His experience indicates that, "for undergraduates there is a clear distinction in which year of study they are - they will know some things and not others and this can be predicted quite well. For researchers and general public this is harder to predict." This is an extremely beneficial approach to take in my view. In a similar vein, **Phys_122** (a 23 year old PhD student) said it is important to: "think a lot before hand on what to assume the audience knows." He said it is "better to give a simplified talk to non-physicists. On the other hand, specific knowledge needs to be transferred to a scientists audience." However, **Phys_160** (a 52 year old Reader in Theoretical Physics) remarked: "In my experience, no audience feels patronized by the substitution of an appropriate analogy for the 'real thing'."

The physicist David Mermin also advances the view put forward by **Phys_160**. Mermin fervently argues for simplicity and clarity when communicating science to experts, intermediates and novices. In a 1992 *Physics Today* article he gives tongue-in-cheek *"Advice to Beginning Physics Speakers (and Intermediate or Advanced Ones)."* Through the voice of a fictitious character, Prof. William A. Mozart, he says:

> "Never, ever, have I heard anybody complain about a talk on the grounds that 'I understood everything in it.' People feel good after talks they can understand. Even those few people who hear nothing they didn't already know can derive substantial enjoyment from hearing their subject presented well. The most important thing your talk can do for such experts is to give them an opportunity to learn how to do better in their own talks." (Mermin, 1992, p.9)

I share Mermin's view that simplicity and clarity should <u>still</u> be used with an audience of specialists and that one's, "only goal must be to furnish ordinary physicists with some modest glimpse of what sustains your own interest in your subject." (Mermin, 1992, p10). He remarks that, "no matter how detailed you might be tempted to make your talk, it cannot possibly be detailed enough for those few who are knowledgeable enough to appreciate such refinements." Physicists interested in technical details can discuss them with the speaker in private afterwards. Even among specialists, there are differences in what is considered interesting. The anthropologist, Sharon Traweek (1995) has remarked that in the field of high-energy physics, theorists had little access to or knowledge of detectors. Thus, at seminars and conferences, though the experimentalists spend at least one third of their talks providing a detailed description of their detectors: "... the theorists rarely attend carefully to these 'technical details,' referring to them as the 'scotch tape' part of the talk." (Traweek, 1995, pp. 159-160).

I would argue that the way in which physicists' deliver talks at conferences varies between sub-cultures of physicists but also between individuals. Often the approach an individual physicist takes will depend on factors such as:

i. **personality** e.g. how confident they are at public speaking, where they lie on an introvert/extravert scale, whether they like using humour, whether they are defensive;
ii. **style of thinking,** e.g. the degree to which they are mathematical or pictorial/physical thinkers, whether they like to use 'visuals' such as graphs, tables or dynamic computer simulations;
iii. **ranking,** i.e. their position within the group may have a marked affect the speech genre. Those on the lower rungs of the academic ladder may adopt dry, technical speech to give a sense of professionalism and imply that they know what they are talking about despite their youthful appearance;
iv. **how they wish to be perceived,** e.g. whether they are trying to impress, entertain, educate, etc;

6.3 Traweek's analysis of high-energy physicists' social and psychological goals when presenting their work

Traweek has identified some common styles of address among high-energy physicists. In Traweek's experience (as an anthropologist and sociologist of science):

> "Experimental high energy physicists usually do their talks at conferences with the lights off, the 'overhead' projector on, and their backs to us, *not,* as ethologists [i.e. animal behaviourists] might surmise, a sign of submission, but as an authoritative gesture. They turn away from us to the illuminated facts as a priest might turn to the altar, and they speak to us in that masterful voice of authority and with that rather patronizing tone of certainty. Often their 'transparencies' are handwritten, deliberately, as proof that the enlightened facts we are reading were so recently gleaned that word of their discovery was confirmed only a few moments ago in a telephone call received from the laboratory." (Traweek, 1995, p. 218)

Traweek may indeed be correct in her interpretation of physicists' motivations for delivering their talks in such an authoritative manner. There are, however, many alternative explanations for this behaviour. For example:

(i) **Lights off and their backs to the audience:**

It is usually easier to see the data being displayed if the lights are turned down low. Also, for someone who is not confident speaking in public, it can be a relief not to have to face one's audience from time to time and the audience may be less distracting if they melt into the darkness. If physicists are using an overhead projector to display their data (as opposed to reading a paper or using a laptop), they may <u>have</u> to turn around to see it properly. I would not advocate turning 180 degrees away from one's audience but would advise standing to the side of a projected image, turning 90 degrees and pointing at a projected image with a wooden or laser pointer. In my experience, an audience's gaze usually follows that of the speaker and this technique is a very useful way of focusing the audience's attention on the object of interest.

(ii) **Masterful voice of authority/patronizing tone of certainty**:

If a physicist doesn't display confidence in his/her own research, other physicists won't either. In fact, Traweek makes this very point in her book, **Beamtimes and Lifetimes,** when she says: "Persuasion is a critical skill. I have been told of interesting experiments that no-one has bothered to corroborate because 'the group didn't go out talking about their work. If they don't believe in their work, why should we?'." (Traweek, 1988 p. 118)

(iii) **handwritten transparencies:**

It is ten years since Traweek made these comments in *"Choreographing History"*, so one could surmise that high-energy physicists no longer use handwritten transparencies to the same extent, preferring instead to use presentation tools such as 'powerpoint'. However, a cursory glance at the on-line proceedings of physics conferences reveals that there are still many physicists who prefer to use handwritten transparencies when presenting their work to peers. Often, they are the more renowned physicists. As mentioned in section 5.6.1, Ed Witten, one of the greatest of contemporary theoretical physicists presented his work on two separate occasions at the **Strings** 2003 Conference, held in Kyoto, Japan in June 2003.[110] First, he spoke to an audience of physicists with **specialised knowledge** of string theory, then to an audience containing a large proportion of local people with a **non-specialised knowledge** of physics.

When communicating with peers he hand wrote on the transparencies as he spoke. I would argue that if a physicist is thoroughly grounded in the details of the material, and feels confident delivering his material 'live' (as Witten certainly is), it may be simpler and quicker to sketch things out by hand. Anyone who has used a program like *Equation Editor* will know that subscripts, superscripts and Greek letters are time-consuming to insert electronically. Not to mention dealing with Feynman diagrams!

Thus, physicists may use hand written transparencies, not as Traweek contends to give the impression of their 'up-to-datedness', but simply because it requires less preparation time. Simple diagrams are sufficient for Witten's task (he begins by reviewing proton decay from the viewpoint of grand unification) because the audience he is communicating with have sufficient expertise in the field to be able to read the diagrams. As mentioned in section 1.17, reading a diagram involves learning conventions. In this instance, the convention that with Feynman diagrams, virtual particles are represented by wavy or broken lines and have no arrows, and that the time axis generally points upward and the space axis to the right, unless one is a particle physicist, in which case they may take the reverse orientation.

Note that the analogy Witten uses in page 4 of his set of transparencies (see fig. 6.1 below) would fit between sets **B** and **C** of my venn diagram (see section 5.5). It is a mathematical analogy, with a medium degree of systematicity, used as a tool of exploration in private conceptualisation and a tool of explanation with expert peers.

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[110] According to the official website, "The **Strings Conference** is held annually, where physicists get together from all over the world to present and discuss new developments of string theory. It consists of invited talks by leading physicists of this field."

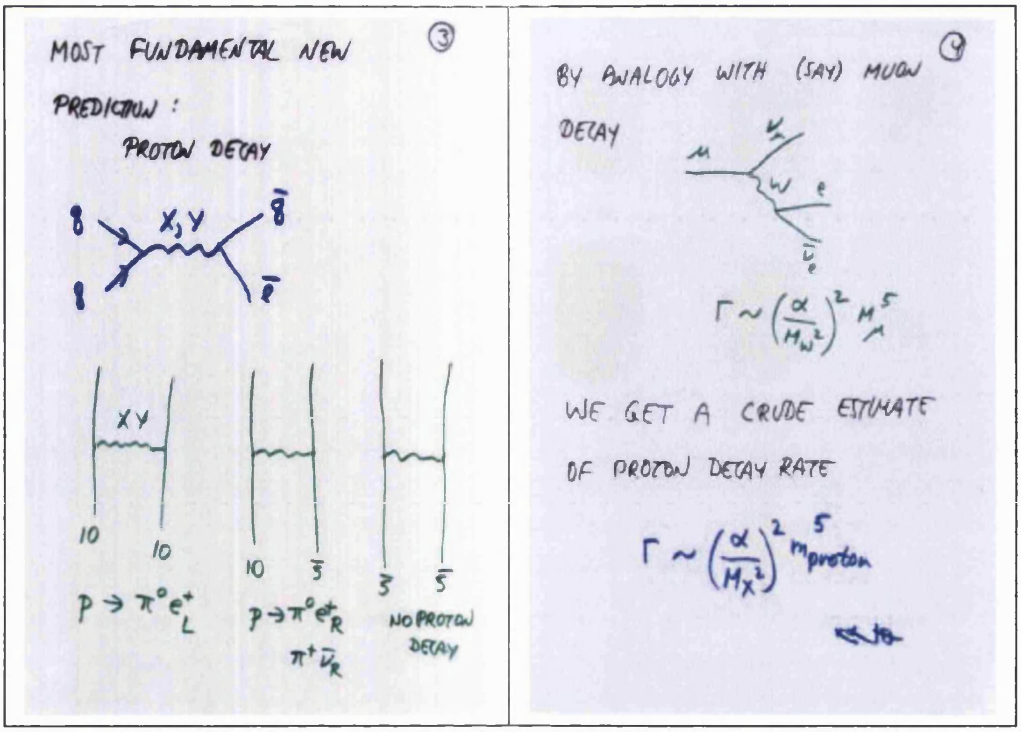

Figure 6.1: Two of the thirty-four hand written transparencies used by Ed Witten during a presentation to his peers entitled, "Proton Decay In Intersecting D-brane Models," at the Strings 2003 Conference held in Kyoto, Japan, July 6th-11, 2003. (Available at http://www2.yukawa.kyoto-u.ac.jp/~str2003/index.html Last accessed 30-03-2006)

When communicating with an audience of local Kyoto residents whose native language was not English, Witten prepared type written transparencies devoid of mathematical notation of any kind. There were no Feynman diagrams, subscripts, superscripts nor Greek letters. (See fig 6.2 below).

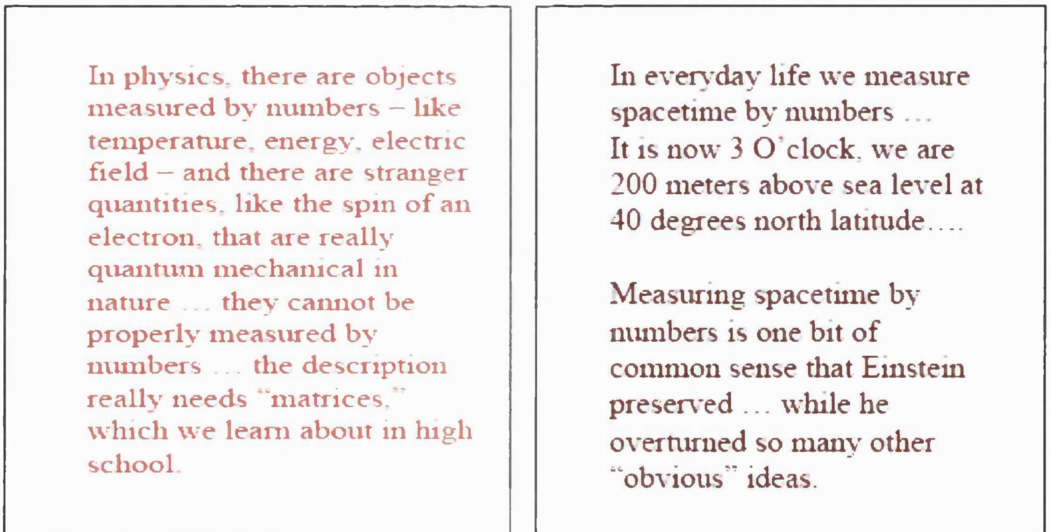

Figure 6.2: Two of the forty typed transparencies used by Ed Witten during a public talk on the "Search for Supersymmetry" at the Strings 2003 conference in Kyoto, Japan. Source:
http://www.yukawa.kyoto-u.ac.jp/contents/seminar/archive/2003/str2003/talks/Witten_pub.pdf
Last accessed: 30-03-200

As we saw in section 4.10, Prof. Berry also strips away technical details and mathematical notation when presenting his pictures to non-experts. However, Prof. Berry still uses images of some kind. In my view, a simple, visual analogy (e.g. of the warping of the fabric of spacetime around a black hole) would have added to Witten's presentation to non-experts (fig. 6.2 above). [111] As we will see in subsequent sections, a majority of respondents indicated that physical and pictorial analogies can greatly enhance a presentation when communicating with non-experts. This technique makes physics more accessible by building on the audience's existing knowledge. However, one must always be careful not to over-simplify the subject and promote a naïve interpretation.

6.4 Respondents' use of analogy when communicating physics with different audiences.

The questionnaire data on the degree to which respondents use analogy when communicating with groups of varying expertise and background was somewhat difficult to unravel. There were two related questions:

Q5. "How often do you communicate physics with the following groups:"

- *(i) colleagues in your own research area*
- *(ii) peers from a competing research group*
- *(iii) physicists from another branch*
- *(iv) scientists from a different discipline*
- *(v) post-graduate students*
- *(vi) graduate students considering doing a PhD in area*
- *(vii) under-graduate students*
- *(viii) The general public*

Q5b. "Do you ever use analogy when communicating with the following groups…"

(i) to (viii) as above.

[111] On the issue of making physics accessible to people of all levels of expertise, I would argue that **legible fonts** are perhaps the most important means of doing this! Witten used of a variety of different font colours on his overhead slides, many of which were difficult to read. This detracted from the clarity of his presentation. I believe strongly that anyone who uses typewritten transparencies or 'powerpoint' slides to present their work should take advice on the most appropriate colour formats, as many people suffer varying degrees of visual impairment (cf Arditi, 2005).

The quantitative selections and written comments from the on-line questionnaire revealed that that analogy was used to a greater extent with audiences having less physics expertise, and in more informal settings.

As some respondents had little or no experience of communicating with some groups their responses to Q5b. may have been biased.

For example, if a respondent rarely communicates with the public, their responses to Q5b. may be rated lower on the 7-point scale because they factor in the frequency of communication with their tendency to use analogy.

A better way of phrasing Q5b would have been to use the conditional tense and ask: *"to what extent **would** you use analogy **if** you were communicating with the following groups?"*

Thus, the large standard deviations (see table 6.1) may be due to physicists' uncertainty over how to interpret or define analogy or to their unfamiliarity with communicating physics with these groups.

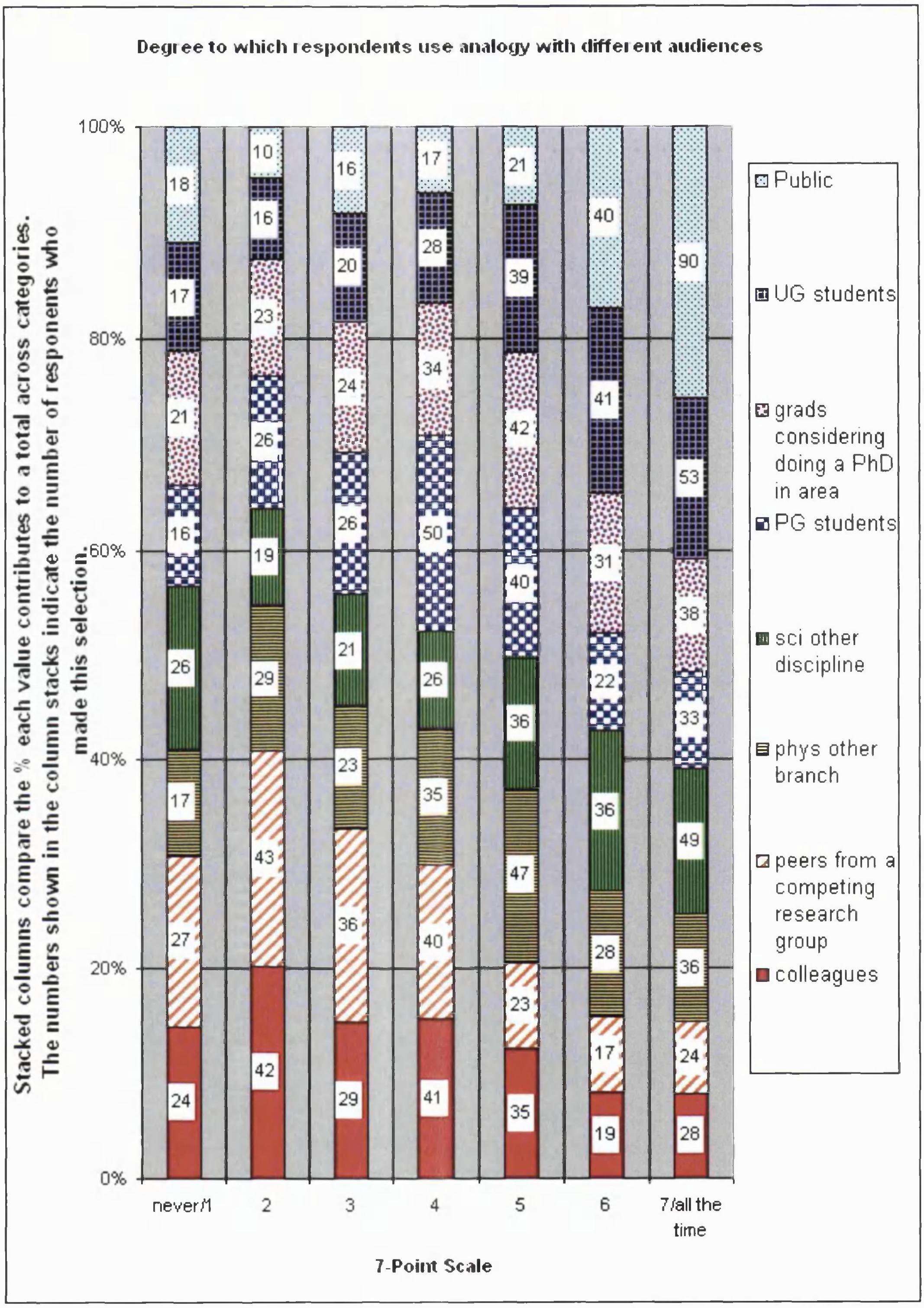

Figure 6.3: Chart showing extent to which respondents' use analogy when communicating with groups having differing levels of physics expertise and academic status.

Q.5b. Do you ever use analogies when communicating physics with the following groups?	colleagues in your own research area	peers from a competing research group	physicists from another branch	scientists from a different discipline	post-graduate students	graduate students considering doing a PhD in area	under-graduate students	The general public
Physicists were asked to select from a 7-point semantic, differential scale which ran from "never/1 – 2 – 3 – 4 – 5 – 6 – 7/all the time"								
Valid responses	218	210	215	213	213	213	214	212
No response	7	15	10	12	12	12	11	13
Mean	**3.87**	**3.65**	**4.37**	**4.55**	**4.27**	**4.40**	**4.83**	**5.33**
Median	4	3	5	5	4	5	5	6
Mode	2	2	5	7	4	5	7	7
Std. Deviation	1.89	1.87	1.87	2.05	1.80	1.92	1.90	1.99

Table 6.1: Statistical information on the degree to which respondents use analogy when communicating with various groups of experts and novices

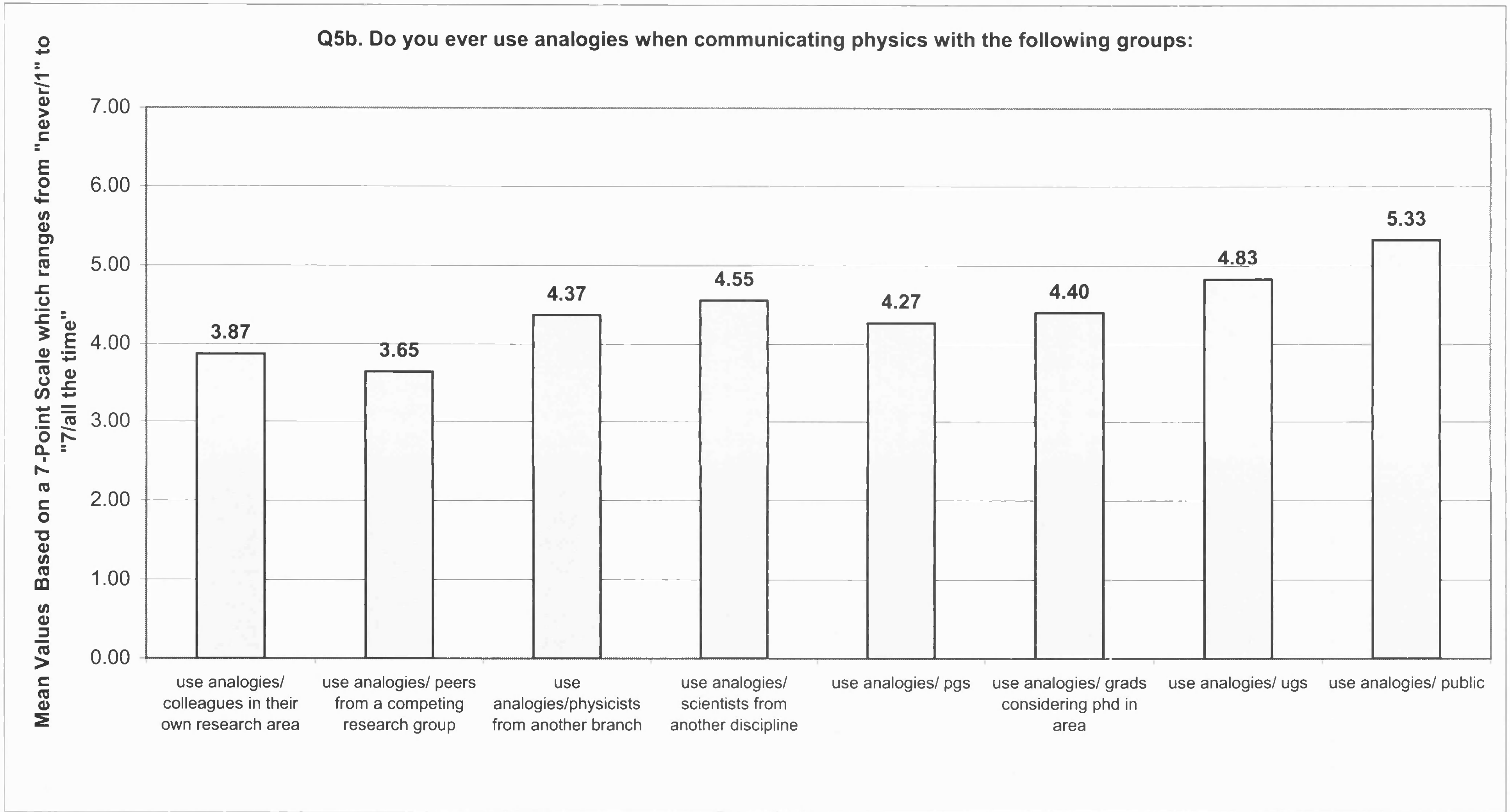

Figure 6.4: Chart showing mean values for respondents' 7-point scale selections regarding the extent to which they use analogies when communicating with eight different audiences, listed on the x-axis.

One could offer some tentative hypotheses on the reasons behind the variation in mean values. For example, that they are lowest **(3.65)** when communicating with ***peers from a competing research group*** because analogy is avoided when the objective is to sound authoritative and rigorous. When analogies are used in this context they are more likely to be abstract, mathematical analogies, lying within set **C** of my venn diagram's system of classification. (See figure 5.3, in section 5.5). The mean value increases **(3.87)** when dealing with ***colleagues in one's own research area***, because although one is dealing with an expert audience, the setting is more informal. As **Phys_95** (a 27 year old, male PhD student) remarked: "For a rigorous, 'dry' explanation, it is best to steer clear of analogies. In a more relaxed setting, it's much more fun to let the imagination run a bit and come up with parallels! Hence the tone of a discussion affects how much I use analogous visualisations..." When analogies are used in this context they can span sets **A, B** and **C**. The mean value increases again **(4.37)** when communicating with ***physicists from a different branch*** because analogy is being used to transfer knowledge across sub-disciplinary boundaries of expertise. These kinds of analogies would fall within the intersection between sets **B** and **C** in my venn diagram's system of classification. The mean value increases further **(4.55)** when communicating with ***scientists from a different discipline*** because in this scenario physicists must find a vehicle that will allow them to transfer knowledge across disciplinary boundaries of expertise. Again, the analogies would be similar to those within set **B**, having physical and pictorial components with medium-level systematicity. The mean value drops back down **(4.27)** when communicating with ***postgraduate students*** because they have probably been trained in the same discipline and are likely to be familiar with the concepts being communicated to them. The mean value begins to increase again **(4.40)** when communicating with ***graduate students who are considering doing a PhD in the respondent's research area*** because analogy is also being employed as a rhetorical tool to make the topic sound interesting, accessible and perhaps even fun. The mean value increases further **(4.83)** when communicating with ***undergraduate students*** because not only does the speaker wish to make the topic sound interesting, s/he also wishes to transfer knowledge to an audience having less physics expertise than almost all of the previously mentioned groups. Finally, the mean value is highest **(5.33)** when communicating with ***the general public*** because this audience has little expertise, the setting is informal, and the objective is usually to inform, educate and entertain. In the last context, the analogies tend to be similar to those within set **A** of my venn diagram. Their components are drawn from everyday concepts and experiences. They are often playful but rarely expressed using mathematical notation as this would not be accessible to the general public.

6.5 Degree to which *level of expertise* affects physicists' use of analogy:

According to Barrow (1992, p.21):"[I]f we look more closely at what scientists do, it is possible to see their descriptions as the search for analogies that differ from those used as a popularising device only by the degree of sophistication and precision with which they can be endowed." The findings presented in chapter 5 support this view. I argued that the analogies used by physicists could be divided into three main sets (A, B and C) where the form of the analogies varied depending on their context of use. Simple analogies (with physical and pictorial features) were more common in the early stages of a physicist's private conceptualisations, when communicating physics to peers in very relaxed settings or to novices in all settings. Complex analogies (with mathematical features) tended to be used as structured tools of exploration in research and as tools of explanation when communicating with experts. Thus, **Q5c** of the on-line questionnaire asked:

> *"Do the following factors influence your use of analogy when communicating with your target audience?*
>
> - *Physics expertise of target audience;*
> - *Academic status of target audience;*[112]
> - *Nationality of (majority of) target audience.*
> - *Other (please state).*

Respondents were asked to select from a drop down menu, which ranged of the from: *"not at all/1 – 2 - 3 – 4 – 5 – 6 7/very much so"*. The quantitative responses to "physics expertise of target audience" are plotted in figure 6.5 below.

[112] the meaning of 'academic status' caused some confusion amongst respondents so was changed to "Prestige of Occasion" after the first 50 replies were received. Unfortunately this also caused confusion for the next 175 respondents, so the data must be interpreted in light of this.

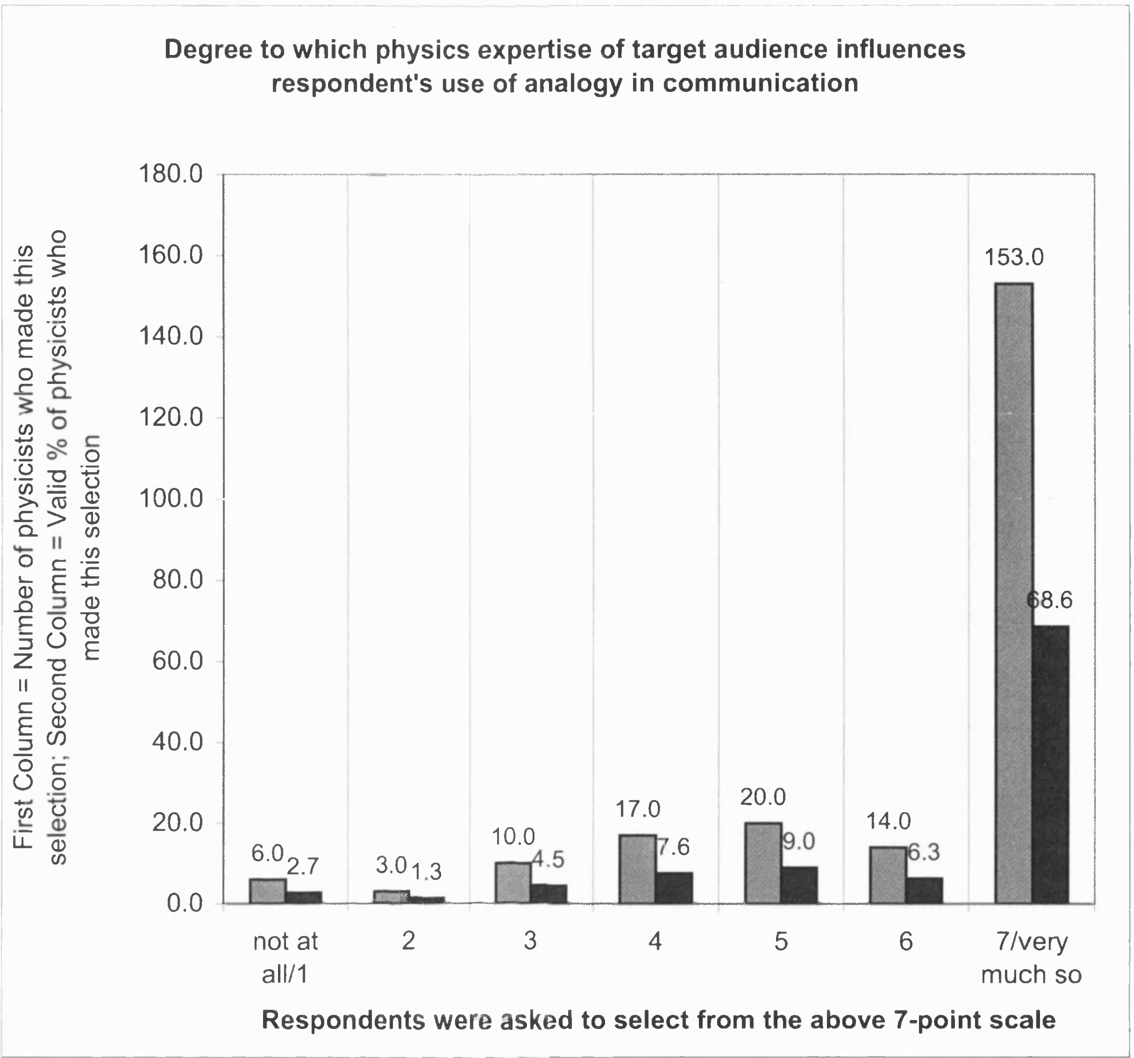

Figure 6.5: Chart showing the extent to which "Physics Expertise of Target Audience" influences respondents' use of analogy when communicating physics.

Quantitative analysis indicates that the physics expertise of the target audience has a huge influence on respondents' use of analogy when communicating physics. Qualitative analysis reveals a range of interesting explanations to account for the influence which expertise of target audience has on physicists' use of analogy. These have been re-coded and their frequencies ascertained. This is presented below:

(i)	More expertise means less need for analogy (analogy may seem patronising)	43.1%
(ii)	More expertise means more complex analogies can be employed	21.3%
(iii)	[Failed to give a reason as to why audience expertise influences use of analogy]	17.8%
(iv)	Talk must be tailored to audience's background knowledge	12.4%
(v)	[Vague Replies]	2.2%
(vi)	Expertise is irrelevant	1.8%
(vii)	More expertise implies a more complicated subject, which makes it more difficult to generate analogies	1.3%

The largest single group (accounting for 43.1% of respondents) said that the need for analogy decreases as the expertise of the audience increases. Some of these respondents specifically referred to the fact that an audience of experts may find analogy patronising. On the other hand, the second largest group (21.3%) said that one may employ more elaborate analogies as the expertise of one's target audience increases. These 48 physicists thus deviate from the popular view: that the degree to which analogy is used is inversely proportional to the expertise of the target audience. However, as discussed in the previous chapter, I believe that respondents had different definitions of 'analogy' in mind when they made their selections. This is despite the fact that 5 different examples of analogy were supplied to respondents to encourage them to take a broad view. For many physicists, analogy appeared to be associated with simplified models used in secondary school problem solving, popular science books, and science documentaries. I believe that respondents in the largest group (43.1%) did not consider formal mathematical analogies when giving their reply, unlike the second largest group (21.3%) who appear to have held a broader view of analogy: that "analogies" include (i) playful analogies; (ii) analogies in the form of physical and pictorial heuristics; and (iii) formal mathematical analogies with a high degree of isomorphism. Thus, I would argue that the quantitative and qualitative data suggests that respondents' **do** consider Bahktinian 'addressivity' when they are communicating physics, although they may not have expressed it within this theoretical framework.

6.5.1 Analogy is used <u>less</u> as the audience's physics expertise increases:

Based on the findings of my pilot studies (Muldoon, 2002), I hypothesised that the common perception amongst respondents to the on-line questionnaire would be that analogy is a particularly useful communication tool when popularising science to the public but isn't always appropriate when communicating their research to experts. As expected, a majority of respondents indicated that they would use analogy less as their audience's level of physics expertise increased.

For example, **Phys_33** (a 47 year old "chief physicist") said simply that the, "need for analogies decreases when physics knowledge increases." **Phys_ 86** (a 36 year old Spacecraft Operations Engineer) said: "An analogy is only useful when it allows people to visualise some concept which they are unfamiliar with in terms of one which they are familiar with... A highly physics illiterate audience (ie the general public) will require the use of a lot analogies and oversimplification whereas peers would require very little, since you could talk on the same terms." **Phys_111** (a 27 year old PhD student) said that: "The language and terminology used tends to be different when communicating with different groups." **Phys_ 97** (a 22 year old PhD student) said: "When talking to people with no physics background it's easier say to analogise, say, spacetime as a rubber sheet which curves when you put masses on it, rather than talking about tensors, metrics and covariant derivatives, which would mean absolutely nothing to them." **Phys_147** (a 25 year old PhD student) said that: "The level of detail will certainly depend on how much knowledge of physics the audience has. Simplified descriptions of e.g. electromagnetic showers would be appropriate for undergraduates/A-Level students, perhaps employing some form of analogy, whereas more detailed and technical descriptions would be appropriate at, say, a conference." **Phys_8**, (a 25 year old assistant lecturer) said: "the greater the expertise, the less need for an analogy. It, in fact, can confuse your argument and lead to scepticism." This mention of 'scepticism' is developed further in section 6.6 where I show that there appears to be a relationship between respondents' wariness of using analogies and their ages: younger physicists wish to impress their superiors by using a more technical mode of communication. On the other hand, more experienced researchers, who have already established the merit of their work, sometimes feel freer to use inexact and playful modes of communication with experts.

6.5.2 <u>More complex</u> analogies are used as the audience's physics expertise increases:
Although a majority of respondents indicated that they would use analogy <u>less</u> as the audience's level of physics expertise increased, several respondents said that they would use analogy to the same extent with experts, but they would use <u>more complex</u> analogies. These analogies would fall within set **C** in my venn diagram (figure 5.3). They are often expressed mathematically. They hold for a hierarchy of relations, from the underlying mathematical structure, to physical and pictorial manifestations of the analogy.

For example, **Phys_127** (a 24 year old PhD student working on high energy particle physics, said that, "Inexact analogies are out of place for physics-expert audiences since they are equipped to understand the 'proper' version. Rock solid analogies are still good, though." **Phys_200**, (a 61 year old, semi-retired, self employed, cement industry consultant) said that, "the use of an analogy is basic to the way I work and think and hence I use analogies of increasing complexity as my audience becomes more technical and science based." Similarly, **Phys_114**, (a 59 year old, Professor of Physics, whose research interests include quantum information theory and the foundations of quantum mechanics) said that with a more expert audience, "this increases the available repertoire of possible analogies." **Phys_21** (a 30 year old lecturer in the area of astrophysics) said that, "If the audience knows a lot of physics then the analogies can be drawn from other areas of physics, if not then they can only be drawn from every-day life. " Similarly, **Phys_177** (a 24 year old PhD student in the area of quantum communication) said that when: "talking to general public, you better use analogies that have something to do with their life. Physicists can understand analogies to their specific field of work." The comments of **Phys_160** (a 52 year old Reader in Theoretical Physics) suggest that he uses analogies with form and function in sets **A, B** and **C** of figure 5.3.[113] First, in his own area of specialisation there are "shared analogies" that he "probably make[s] use of without necessarily realising" he is doing so, i.e. analogies in set C possibly intersecting with set **B**. Second, when talking to physicists with other specializations he says "I typically draw on analogies between what I do and what they do." These are analogies in set **B**, and to a lesser degree, the intersection between **B** and **C**. Third, he uses "everyday" analogies with non-physicists, i.e. set **A**.

These findings provide supporting evidence for the hypothesis that many respondents interpreted the term 'analogy' differently. Respondents who said they use <u>less</u> analogies as the audience's physics-expertise increases probably held a narrower interpretation of analogy which did not encompass formal, mathematical analogies? It is also possible that respondents had different (more or less sophisticated) views of their target audiences or contexts of use, perhaps on account of their relative experience or inexperience. It is also possible that there is a dearth of sophisticated analogies in certain areas of physics. For example, some respondents claimed that it was too difficult to formulate analogies in their research area. Or perhaps those who use analogies of increasing sophistication as the physics expertise of their audience increases are more adept at formulating analogies.

To answer these questions it would have been necessary to recode the qualitative data and test for correlations. However, as there were a large number of blank replies, nothing conclusive could have been obtained from that data. I decided to focus on this issue in the follow-up correspondence with the 70% of respondents who agreed to be contacted in the future. Unfortunately, those that left blank replies tended be less willing to be contacted in the future so it was difficult to completely clarify the matter without a full round of re-sampling and re-testing. However, the results of my follow-up e-mail exchanges show that the physicists I surveyed are sensitive to <u>context</u> and <u>audience</u> in their use of analogy. This is also borne out in my January 2004 interview with Dr. Lawson, who

[113] "People I talk to are divided quite sharply into two groups: those who work in roughly the same area as I do, and those who know very little about what I do. Within my own area, there are shared analogies that I probably make use of without necessarily realizing that I am doing so. When talking to physicists with other specializations, I typically draw on analogies between what I do and what they do. On the rare occasions that I discuss my work with non-physicists, I make use of everyday analogies to the extent that that is possible."

said that his use of analogy was highly dependent on the context and audience. For example, he said that if you are dealing with "a fairly **sophisticated** physicist, you can take a **sophisticated** analogy;" With "the general public" on the other hand, "it's very often helpful to find a **very simple** analogy to things that they're **familiar with**." [114] Dr. Lawson agreed that the complexity of the analogy would increase directly proportionally to the expertise of the audience. Thus, Dr. Lawson's experiences of using analogy to communicate physics are in line with 12% of questionnaire respondents who highlighted the need to tailor the talk to the audience's background knowledge, and 21% of questionnaire respondents who said that the complexity of the analogy tended to increase directly proportionally to the expertise of the audience.

6.6 Degree to which academic status or prestige of occasion (or tone of discussion) influences physicists' use of analogy.

Fear of misleading one's audience is not the only deterrent in using analogy in communication; fear of being looked down upon is also a factor. In all areas of communication, one must mould one's speech to the tone of the discussion. For example, the tone adopted when speaking about one's research to one's friends in the pub will probably differ from speaking about one's research at a departmental seminar (even though the same friends may make up 90% of the audience). The presence of one's head of department e.g. will probably make certain (witty, humorous, self-deprecating) comments less 'appropriate'. Gauging the tone can be difficult. It depends on one's own perception of what is 'normal' and 'appropriate'. Personally I appreciate the use of humour to make topics more engaging. Many individuals, however, consider it unprofessional to employ humour in scholarly work. Essentially it revolves around two issues: projecting an appropriate image of oneself and not wishing to offend experts. The common perception is that if one wishes to be taken seriously in an academic setting, one must adopt a professional approach, upholding the standards and traditions of the field. Use of dry and technical speech is believed to be a safe way to project a professional image and thereby climb the rungs of the academic ladder. The quantitative data does not at first glance support this hypothesis as the majority group say that the prestige of the occasion would in no way influence their use of analogy. (See figure 6.6 below).

[114] Dr. Lawson in conversation with Ciara Muldoon, Jan 2004.

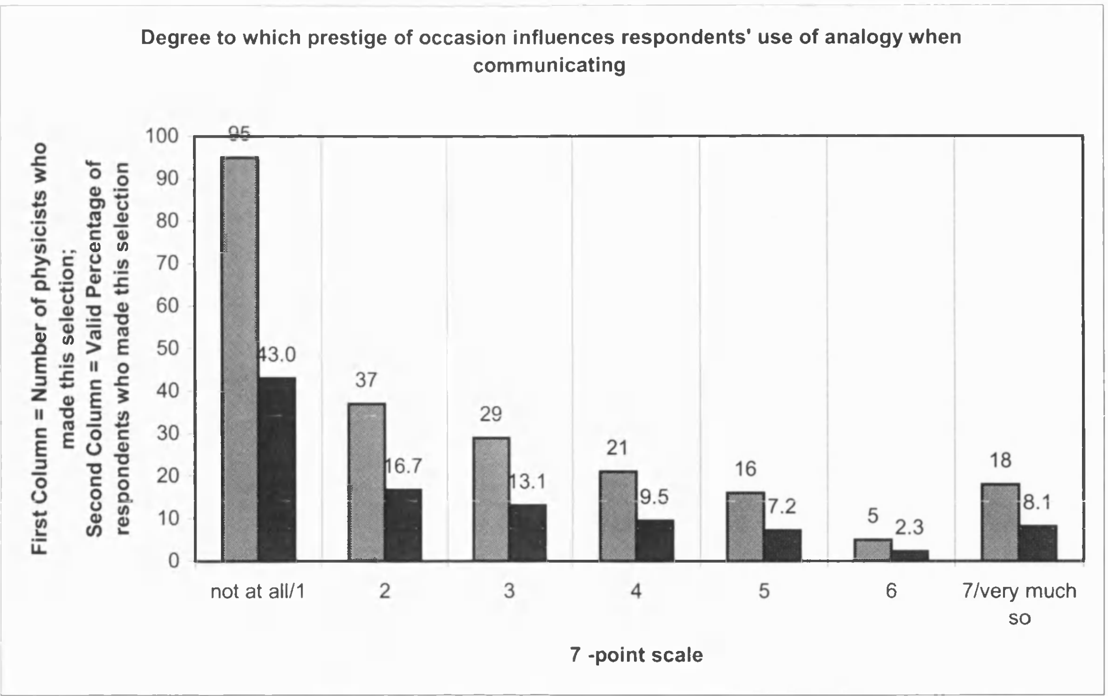

Figure 6.6: Chart showing the degree to which prestige of occasion influences physicists use of analogy when communicating with their target audience

However, upon further examination, it becomes evident that the wording of the question was quite confusing which resulted in many failures to elaborate. Many respondents also had little experience communicating at so-called 'prestigious occasions' and consequently could not comment. It is difficult to investigate the extent to which social setting influences behaviour. Such concerns are often sub-conscious. Even when an individual is conscious of them they may not wish to openly acknowledge that they have this concern. Written comments were re-coded according to certain common themes and their frequency of occurrence ascertained. This is presented below:

(i)	[No comment]	**24.9%**
(ii)	Academic Status/Prestige of Occasion is <u>irrelevant</u> - would still use analogies	**24.0%**
(iii)	Prestigious Occasions tend to be more PR orientated => more analogies	**6.0%**
(iv)	On more prestigious occasions I would try for <u>more original</u> analogies	**6.2%**
(v)	I have no experience of this	**2.7%**
(vi)	It depends on what audience knows and how they're inclined to listen	**0.9%**
(vii)	<u>Less spontaneous</u> in use of analogies on more prestigious occasions	**0.9%**

The meaning of these figures is explained in sections 6.6.1 and 6.6.2, drawing on respondents written comments. (See appendix 6, section A6.1 for additional comments.)

6.6.1 analogy is looked down upon in formal settings:

The use of amusing and playful analogies, and other creative use of language are considered by many physicists to be appropriate in informal settings, but less appropriate in more formal settings. For example, when asked whether the "prestige of the occasion" might influence their use of analogy with their target audience, **Phys_93** (a 32 year old research fellow involved in quantum cryptography) said: "This is important. In an informal discussion, where a problem is analysed sometimes only in a few minutes, analogies help a lot. For a formal talk its better to be more professional." The state of development of the community of practitioners may also play a part. According to Bissel and Dillion (2000, p.10): "... in less secure areas, in communities whose boundaries are changing or whose members feel vulnerable to external criticism, there is an emphasis on formality that is a direct result of perceived external pressures."

According to **Phys_36**, (a 24 year old PhD student involved in space science): "analogy is occasionally 'looked down upon' in a formal scientific situation." His implication is that analogy is too simplistic and imprecise to use with experts. Similarly, **Phys_90** (a 25 year old PhD student involved in particle physics) said that it was a catch-22 situation when an audience is composed of individuals with varying levels of expertise, as he put it: "Experts will often feel insulted by what they feel are simple-minded analogies. Even if they do not, they may think less of your capabilities. On the other hand, it's important to help those who don't know the areas as well to understand as easily as possible." Likewise, **Phys_9** (a 32 year old lecturer in physics and astronomy) said that: "Analogies may be perceived as a dumbing-down, humorisation or over-simplification of a concept; therefore they need to be used with care if the audience is already expert or 'stuffy'." **Phys_14** (a 53 year old professor of physics in the area of surface science technology) said: "At conferences of experts, I usually find analogies less useful and less comfortable to use." **Phys_29** (a 42 year old researcher in the area of astrophysics) said: "I do not like to use too many analogies at a high power conference because analogies are sometimes perceived as a crutch for the inarticulate."

As mentioned previously, the manner in which one communicates is of course dependent on one's character – introvert or extrovert, insecure or confident, comical or droll; on one's own preferences for visual, verbal, or mathematical explanations; etc. However, there appeared to be some correlation between respondents' **age** and the degree to which prestige of occasion was influential. (See table 6.2 on the next page). Respondents in the 19-29 year old age-bracket seemed to be the most influenced. Positioned as they are, lower down the academic ladder, these physicists may feel more insecure about their abilities and more inclined to impress their superiors. However this age group did have the least experience of presenting at prestigious occasions so their comments were more conjectural. Also, these respondents may have held a narrower interpretation of analogy, which excluded formal, mathematical analogies. Taking all this into account, it is, in my opinion, easier for esteemed physicists to employ less formal analogies in communication because they have nothing to prove. Unlike younger, 'unknowns', esteemed researchers have confidence: their work is highly regarded so they can afford to be more informal in their presentations. **Phys_68** (a 44 year old reader in physics) said that in his experience: "I find that even amongst distinguished colleagues it is better to give a picture that everyone can understand. I have seen this done by the most eminent in the field, and everyone appreciates that they can understand what is going on."

ID	**Age (years)**	**Gender**	**Research Position**	**Response to question concerning academic status (0- 50) and re-worded prestige of occasion (51-225).**
Phys_13	32	female	lecturer	"Probably don't want to make it seem too easy!!"
Phys_20	23	male	PhD student	"Depending on audience, presentations will be altered to suit. Don't want to be patronising to those more qualified, but don't want to leave others behind during the talk."
Phys_27	25	male	PhD student	"You want the people who give you money now or who might give you a job later on to think you are smart, not that you are a playschool presenter."
Phys_30	23	male	PhD student	"Must understand your position in the rank of the research world".
Phys_145	27	-	research fellow	"I have limited experience of this but I am more careful with my wording!"
Phys_176	24	male	PhD student	"perhaps i'd avoid more simplistic analogies if the audience contained distinguished physicists!".
Phys_187	26	male	PhD student	"Don't want my research to seem over simplistic."

Table 6.2: showing that there appears to be a relationship between respondents' age and the degree to which prestige of occasion was influential, with younger respondents being wary of offending experts by using analogies.

6.6.2 Eminent Physicists' Use of Analogy: Kroemer's Nobel Prize Address

Following on from the comments of **Phys_68**, I thought it would be interesting to analyse a sample of Nobel Prize speeches (or equivalent) to see if there is any evidence to support this hypothesis. What little exploration I have done, suggests that non-formal analogies, (and other forms of simplified visualizations), are often employed by physicists in their Nobel Prize addresses. For example, in 2000, Alferov, Kroemer, and Kilby shared the Nobel Prize In Physics.[115] Kroemer has a famous adage:

- **Kroemer's Lemma of Proven Ignorance:** "If, in discussing a semiconductor problem, you cannot draw an Energy Band Diagram, then you don't know what you are talking about."
- **Induced-Ignorance Corrollary to Kroemer's Lemma of Proven Ignorance:** "If you can, but don't, then your audience won't know what you are talking about."

In a b*and diagram* arrows indicate forces, the slope indicates elementary charge times field, and the electrons and holes simply respond to the slope of the band edges. Early in his Nobel address, Kroemer quoted his *Lemma of Proven Ignorance* (Kroemer, 2000, web ref.) and accompanied it with a series of simplified band diagrams, as shown in figure 6.7.

Herbert Kroemer 451

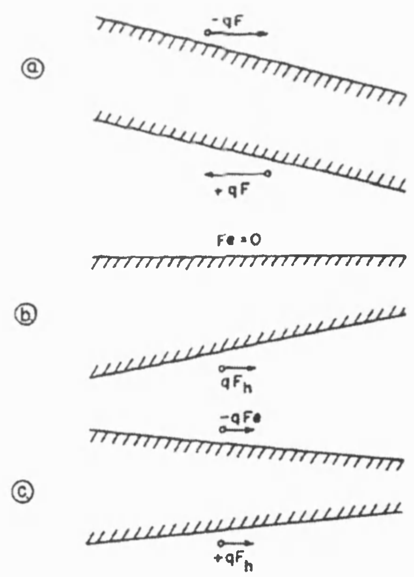

Figure 1. Quasi-Electric Fields: (a) A true electric field simply tilts the bands; (b) quasi-electric fields, with no force on electrons, but a force on holes; (c) quasi-electric fields forcing electrons and holes in the same direction. From Kroemer (1957a).

Figure 6.7: Image of band diagram used by Kroemer (2000) in his Nobel address.

[115] "for basic work on information and communication technology" , "for developing semiconductor heterostructures used in high-speed- and opto-electronics" and "for his part in the invention of the integrated circuit" respectively.

Kroemer then went on to use a simple expository analogy:

> "Electrons are being driven to the right – they are behaving like water on a sloped surface. Holes are being driven to the left – they behave somewhat like bubbles in water, which, of course we all know, rise." (Kroemer, 2000, web ref., 2001)

This analogy has some shortcomings, but could be considered acceptable because the audience is composed of a mixture of novices and experts, from differing disciplines. Also, the majority of Kroemer's Nobel address was actually geared toward an audience with a good knowledge of physics. By beginning from a simple picture, and building up to more technical explanations, Kroemer was able to satisfy most of the audience, introducing the subject to novices and reminding experts of the achievements made.

6.6.3 The importance of play and humour when communicating physics

My findings suggest that successful science communicators often employ humour to make their subject matter engaging. The use of humour and play is delicate however. One cannot be seen to be unprofessional or flippant if one is to project a respectful image to one's peers or superiors. Several respondents highlighted this fact (in response to the question concerning how prestige of occasion might influence use of analogy). **Phys_212,** a postdoctoral researcher said that: "Until one has a permanent job one cannot be too flippant at a formal occasion. Informal talks are different - humour often helps." **Phys_165**, a 36 year old, advanced research fellow, said that the prestige of the occasion: "Might have a small effect. People tell me that the most silly jokes should be omitted in more prestigious occasions and that the pictures should look more fancy."

When communicating with novices, successful physics communicators continuously emphasise the fact that an analogy is an idealisation, not to be taken literally. Some even make light of the fact that people take analogies too literally. In fact, poking fun at people who take analogies too literally is a useful means of warning people of the dangers of being misled by these simplified representations. Professor Paul Coleman of the Physics Department at the University of Bath did this on numerous occasions during his wonderfully engaging inaugural lecture entitled: ***"Probing Matter with Anti-Matter: A Career in Self-Annihilation."*** He used humour to great effect throughout. His opening words drew laughter from the audience and immediately set the tone:

> "Thank you George[116] for that overwhelming introduction - - what I wrote. {Laughter from audience}. Ah, most of you here tonight are probably expecting me to talk for 50-55 minutes; well, because of that I had a trial run this afternoon – 18 and a half

[116] Prof. George Lunt, deputy vice-chancellor.

> minutes. *{Laughter from audience}*. Therefore, I'm going to take a leaf out of Kingsley Amis's book – literally *{he opens the book}*: 'Talk slowly, every third sentence speak loudly, *{laughter from audience}* to give the impression you're saying something important *{laughter from audience}* and interweave your talk with long passages of Portuguese'*{laughter from audience}*. You think I'm joking. *{laughter from audience}*." [117]

Prof. Coleman had the confidence to do this because he is well regarded in his field. However, he was constantly wary of not offending his colleagues through his use of his playful tone or inclusion of simplified analogous visualisations. For example, later in the lecture, while explaining the fate of positrons in matter, he displayed a billiard ball representation of a positron bouncing around an atomic lattice; he stressed the idealised nature of the representation to the novices in the audience and acknowledged that this approach would be frowned upon by experts, remarking: "I must apologise to my scientific colleagues for this billiard ball approach but it's easier to draw than its quantum equivalent." (ibid.) This aside does two things: it reminds novices that this is a simplified version of the physical situation and that experts deal with much more complicated visualisations; by doing this, it ensures that experts do not worry that the novices in the audience are being misled by this overly simplified version of the physical system.

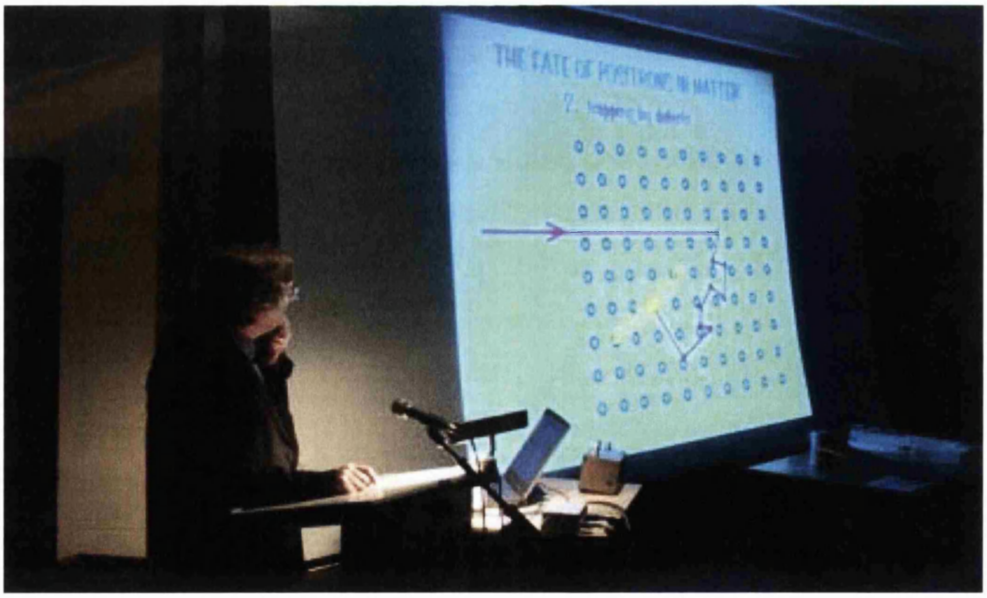

Figure 6.8: Prof. Coleman, during his inaugural lecture.
© Imaging and Photographic Unit, University of Bath.

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[117] Coleman, during his inaugural lecture: ***"Probing Matter with Anti-Matter: A Career in Self-Annihilation,*** " delivered the University of Bath, on 1st May, 2003

Bissel and Dillon (2000, p.6) note that: "Models are starting points for conversations among practitioners about the system they are claimed to represent... As part of their development engineers learn how to talk about their models." I would argue that like engineers, physicists must also "learn what stories to tell about [their models] and to recognise what sorts of conversations are legitimate." (ibid.)

Professor Coleman emphasised the idealised and simplified nature of his billiard ball representation of positronium, on another occasion in his inaugural lecture, saying:

> "Again if my colleagues will forgive me I'll show you- I'll **try** to show you – a billiard ball representation of this. There we are. This is a hydrogen atom with a proton in the middle, and an electron going around it. And this is positronium with the ahm – *positive things are red, you see and the electron is blue as everybody knows* – so here is the electron and the positron going around, but on the same orbit, so it's about the same size as the hydrogen atom, although the distance between the particles is double, in the case of the positronium." (ibid.)

His tongue in cheek remark that "the electron is blue as everybody knows" draws attention to the hugely simplified representations of subatomic particles introduced in textbooks in secondary level education, which often persist with many people, particularly if they have not taken science at a higher level. This is a wonderful example of using humour to highlight the pros and cons of employing analogies in physics.

6.7 The Drawbacks of Analogy: Confusing the Map with the Territory.

The drawbacks in employing analogy in conceptualisation and communication have been outlined by many historians, philosophers, psychologists, and sociologists of science over the past 40 years (e.g. Hesse, 1966; Larkin & McDermott, 1980; Gentner, 1983; Gentner & Gentner, 1983; Nersessian 1995; Holyoak and Thagard, 1996; Taber, 2001). As mentioned in chapter one, Holyoak and Thagard (1995, p.204) caution that: "Without guidance from a teacher, analogy is often a trap for the unwary novice, rather than a stepping stone to expertise." As Hesse (1966) explained, models have *positive analogies* (e.g. the earth orbiting the sun : the electron orbiting the nucleus), *negative analogies* (the size of the sun : the size of the nucleus), and *neutral analogies* (where the relation is not known).

Spiro, Feltovich, Coulson, and Anderson (1989) provide an excellent summary of the dangers of reductive analogies in the intermediate stage between novice and expert. The intermediate's goal is: (a) **mastery of complexity** (going beyond superficial familiarity with simplified versions of concepts) and (b) **knowledge applicability** (the ability to apply or transfer knowledge adaptively). Their examples are derived from medical students' common misconceptions that, in Spiro et al.'s view, are: "traceable to cognitive (and sometimes instructional) overreliance on single analogies." (op cit. p. 499). According to Spiro et al. (op cit. p.515) **single analogies** suffer the following shortcomings which often results in deeply held erroneous knowledge:

(a) information that is missing from the source;

(b) information in the source that is misleading about the topic;

(c) information that is inappropriately focused in the source.

Spiro et al. (1989) identify eight varieties of analogy-induced misconception, and suggest that **multiple analogies** can act as an antidote if they are properly "selected, integrated and psychologically managed." (op. cit. p. 500). What Spiro et al. propound is what they call "non abstractive integration". They explain it thus:

> "By using a *composite* of several analogies, understanding is not abstractively reduced either to a superordinate system or to any one of the analogies acting as privileged with respect to the others. In contrast, in *abstractive integration* the individual elements are *replaced* by a subsumptive abstraction that *stands for* the elements and/or their combinations. By presenting the composite analogies as simultaneous overlapping images, the composite leads to a perceptual integration." (op. cit. p523)

To illustrate this idea they compare it to the perception of complex objects like human faces, where the whole is psychologically graspable without loss of information about parts. One can recognise overall facial expressions or else focus on the components of the face, e.g. distance between the eyes, size of the nose, shape of the mouth etc. They say: "The physiognomy is perceptually integrated while the component parts continue to make their contributions individually (in contrast to the supplanting of individual elements in an abstractive integration)." (ibid.) I support Spiro et al's (1989) call for the "*systematic assembly of multiple knowledge sources* – integrated multiple analogies, compiled fragments from diverse schemata, re-presentations of the same information under different organizational schemes, etc." (opcit. p.529).

In the same volume, Brewer picks up on this idea of 'nonabstractive integration', posing the following provocative question:

> "What is the form of representation of the knowledge of muscle physiology in the case of the true expert? Does the research scientist who studies muscle physiology continue to use 'nonabstractively integrated' instances, or does the information become an integrated abstract structure?" (Brewer, 1989, p.538)

This question could also be asked of *advanced knowledge acquisition* among physics scholars. Respondents to the on-line questionnaire could be classified as intermediate (PhD students), advanced (Post Doctoral Research Associates) and expert (Lecturers and Professors). When conceptualising and communicating physics many of these physicists reported using analogies that are *inconsistent* or *mutually contradictory*. In nuclear physics, for example, physicists use various phenomenological models (founded on formal analogies) - the liquid drop model, the shell model, the compound nucleus model, the optical model - in order to describe scattering, fission etc. The situation is similar in optics where, as Morrison explains, the models', "idealized structure...makes them useful as instruments in the design of lenses and for the calculation of different effects produced in different experimental contexts." (Morrison, 1998, p.73). So while physics students do learn some multiple analogies as antidotes to single analogies which are misleading, incomplete, or inappropriately focused (e.g. flowing waters or teeming crowds for electricity) for the most part, multiple analogies are used as a source of information for practical problem solving at a later date. [118] Once assimilated, the models become part of a physicist's toolkit. As a result of their practicality they are taken by many to be realistic, for all intents and purposes, and cease to be regarded as 'analogies' as such. They are "taken for granted" as **Phys_128** said.

When asked, in Q5d, to what extent the physics expertise of the target audience influenced his use of analogy, **Phys_89** said: "I'd use analogy either with an audience that is very expert in what I'm saying, or with an audience that is totally 'blank'. I'd use less analogy with an intermediate audience, that might be misled." [119] **Phys_89** was the exception in this respect. For the most part, the science communication section of the questionnaire revealed that most physicists believe that 'analogy' (by their definition) is too simplistic, ambiguous and misleading to be used when communicating with experts. It is, in their view, most useful when communicating with novices, (i.e. in popular science talks) or with intermediates (physics students in secondary and early tertiary level education). Use of analogy should, in their view, be inversely proportional to the audiences' physics expertise. Of course this means that those who are least able to evaluate the merits of an analogy are the ones most likely to have analogy thrust upon them. However, the group most at risk of adopting a naïve interpretation are the intermediates. Undergraduate and post-graduate students frequently employ models and analogies in problem solving. We know from Spiro et al's research that even when the **disanalogies** are

[118] As Bruce Gregory puts it, "for a physicist, a realistic picture is far too complex to be useful as a tool, and physics is all about fashioning tools... the world of physics is a world of hard edges and abstraction, a mathematical world as austere and as beautiful as a painting by Mondrian." (Gregory, 1988, p.3)
[119] **Phys_89**, a 28 year old, male, post doc, whose research interests include: "polymer dynamics, interfacial rheology, liquid interfaces, colloidal suspensions."

made explicit to students,[120] many still hold erroneous assumptions, often misled by connotations of non-technical descriptive language. The danger is to confuse the map with the territory. As Alfred Korzybski (1933, p.58) noted: "A map is *not* the territory it represents, but, if correct, it has a similar structure to the territory, which accounts for its usefulness." Use of analogy in science education should not be avoided. As Nersessian remarks, students:

> "posses the basic cognitive capacities employed in constructive modelling: to make analogies, to create mental simulations, to perform idealization and generic abstraction, and this fact can be taken advantage of and cultivated in the domain of science." (Nersessian, 1995, p222 & 205)

Although novices and intermediates possess the basic cognitive capacities employed in constructive modelling, they often lack the skill to judge the scope or appropriateness of an analogy. Thus, physics educators should highlight the limitations of single analogies, and make every effort to use multiple analogies (properly selected) to counteract the omissions and over-extensions of single analogies.

6.7.1 A new approach to the use of analogy in science education?

Firing positrons from a particle accelerator is often likened to firing little blue balls from a gun. To the eyes of a novice, there is significant literal similarity between the source domain (little blue balls being fired from a gun) and target domain (positrons being fired from an accelerator). Without proper guidance, some novices come to think that positrons 'really are' little blue balls. As mentioned in section 6.7, guidance consists of giving students examples of good analogies and counter-examples or exceptions to illustrate the limitations of these analogies.

I believe that original analogies which feature physically **possible** but **implausible** situations may be less likely to cause novices to adopt a naive interpretation of an analogy. For example, instead of comparing positrons to inanimate objects like little blue balls, Professor Paul Coleman's playful explanation of positron surface interactions[121] compares positrons to chickens. It is reproduced and abridged below, with Professor Coleman's kind permission.

[120] albeit medical students in this case, but presumably sharing similar cognitive capacities.
[121] presented at his inaugural lecture: ***"Probing Matter with Anti-Matter: A Career in Self-Annihilation,"*** delivered the University of Bath, on 1st May, 2003

Professor Paul Coleman's *Dazed Chicken Model*:

Imagine a ravine. On one side of the ravine is a forest of evenly spaced trees (analogous to a crystal lattice). Some of the trees have been up-rooted, leaving holes in the ground (analogous to vacancies or defects in the lattice). On the other side of the ravine, chickens are fired from a cannon (analogous to positrons fired from a particle accelerator). The chickens get propelled across the ravine, smashing into the evenly spaced trees. Some stagger around on the ground, completely dazed (analogous to thermal positron diffusion). Some fall into holes in the ground (analogous to trapping by vacancies or defects beneath the surface). Some fall into the ravine (analogous to surface state trapping). Some, not so dazed, fly back across the ravine (analogous to positron re-emission).

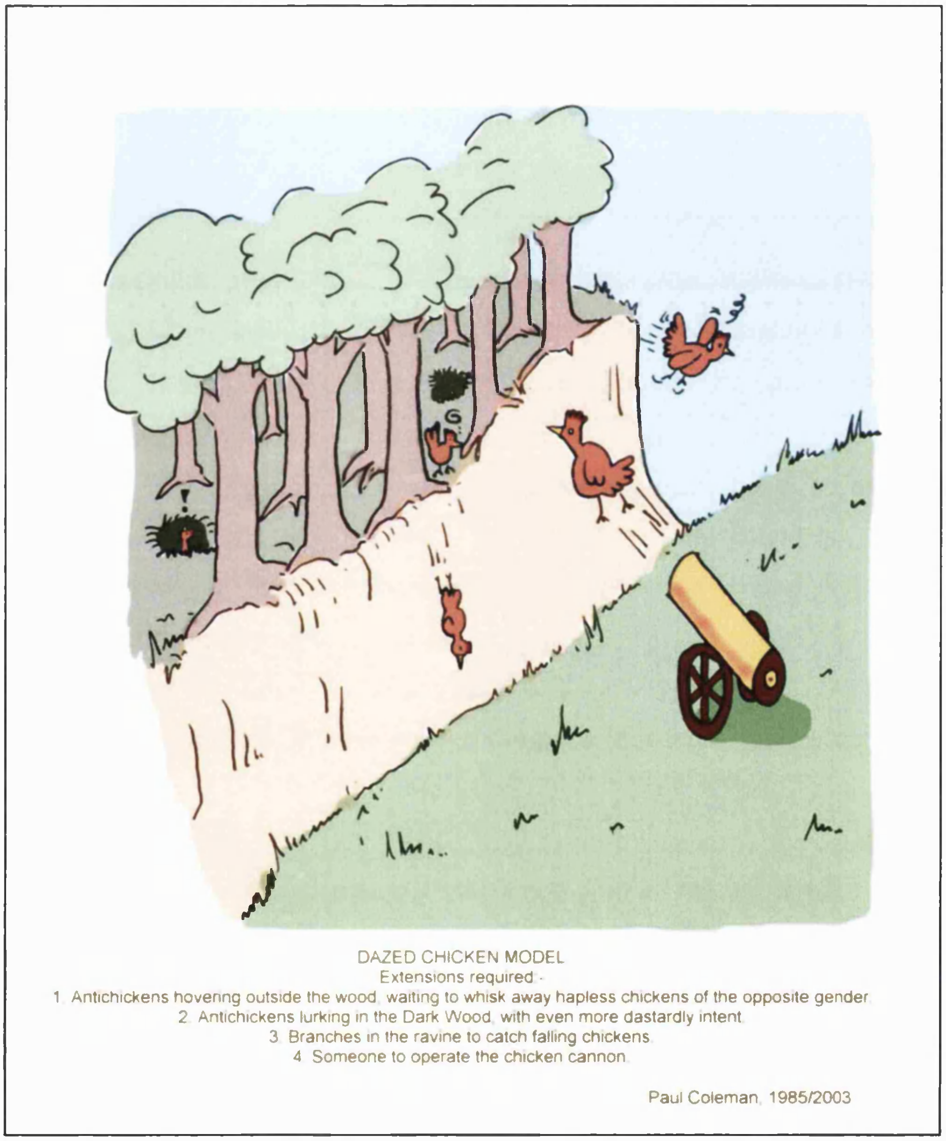

Figure 6.9: Paul Coleman's Dazed Chicken Model.
© Paul Coleman (University of Bath) 1985/2003

The entertaining verbal analogy and accompanying sketch are extremely **accessible and memorable** for physics novices (and intermediates and experts). The analogy could probably work with just a verbal mode of expression but the visual mode makes it much more engaging and memorable. Unlike the standard analogy of little blue balls being fired from a gun, this outlandish analogy also contains **little literal similarity,** thus novices do not adopt a naïve conception of positrons being literally similar to chickens, or an atomic lattice being literally similar to a forest of evenly spaced trees. Although it contains little literal similarity, it does contain **considerable systematicity**: there is a one-to-one correspondence between the elements of the source and target domains for a hierarchy of relations. This ranges from non-literal relations between the source and target on a physical or pictorial level (e.g. chickens being like positrons), down to mathematical relations that exist on a deeper structural level (e.g. the shape of the ravine could be thought of as a mathematical function relating to a potential well in which positrons can be trapped near a solid surface). The physical picture attached to the physically possible but implausible source can thus be used as a bridge to understand the physics of positron surface interactions. The analogy works because it is visually engaging, amusing, memorable and actually holds for a hierarchy of relations. However, like all analogies, it does have limitations. Professor Coleman was very keen to stress this fact. He said to me during one of our follow-up e-mail exchanges:

> "The analogy is far from perfect - the phenomena involved should be described quantum mechanically, for example - and chickens are definitely classical (Newtonian) creatures - but, with the extensions I noted on the original sketch, most areas are covered in some way." [122]

In response to my queries concerning the origins of the analogy, Prof. Coleman explained that he "doodled" the Dazed Chicken Model during a "far from interesting" conference talk. He said:

> "There was no specific cue; I have always liked absurdist humour... My intent was to have some fun and to lighten what was a very boring time. But the sketch has since amused many of my colleagues in positron physics, and I am now using it in a short presentation to potential students and their parents on UCAS [Universities and Colleges Admissions Services] admissions days in the Department." [123]

This is a perfect example of play and humour being used to good effect by a practicing physicist with a flair for communicating with experts and novices. I believe that an analysis of the key features of good or successful analogies, drawing on the practical

[122] (Prof. Coleman, responding to my e-mail query, 07-12-2005)
[123] (Prof. Coleman, responding to my e-mail query, 07-12-2005)

expertise and communicative skills of physicists like Prof. Coleman would be useful to science educators. These would be engaging and memorable but have well-thought out hierarchies of relations which are less likely to mislead novices. As will be discussed in chapter 9, I may compile such a databank in the future, via an on-line system of data retrieval, drawing on the network of physicists I built up in the course of my doctoral work.

6.8 Degree to which the nationality of their target audience influences physicists' use of analogy when communicating physics

The popular science writer J.D. Barrow (1992, p. 21) recounts how:

> "One Hungarian physicist once remarked in the course of writing a textbook that although he would often be referring to the motions and collisions of billiard balls to illustrate the laws of mathematics, he had neither seen nor played this game and his knowledge of it was derived entirely from the study of physics books."

The importance of ensuring that one's audience is familiar with the analogies one employs was highlighted during my pilot studies (Muldoon, 2002) by a physicist from Arizona. He said that he always makes a conscious effort to tailor his talks to the background of his audience. In his own words:

> "The analogies employed vary all the time depending on the physical nature of the subject and the real-world experience of the audience. For instance, an analogy we like to use for the formation time for the columns in the Eagle Nebula HST [Hubble Space Telescope] picture we made is a direct comparison with the formation time of the rock columns in Monument Valley here in Arizona. The interesting part is that size-wise the columns in the nebula are 3 light-years long, compared to the 100's of feet in Monument Valley. But the timescale for formation is only about 200,000 years for the columns in the nebula, and several million years for the columns in Monument Valley. That always works well with the general public. But that's because they all have a mental picture and familiarity with Monument Valley. You try and do that in Budapest and it wouldn't fly. " (Muldoon, 2002, E-mail reply 7, Lines 87- 96)

As mentioned previously, this issue was addressed in question 5c of the on-line questionnaire.

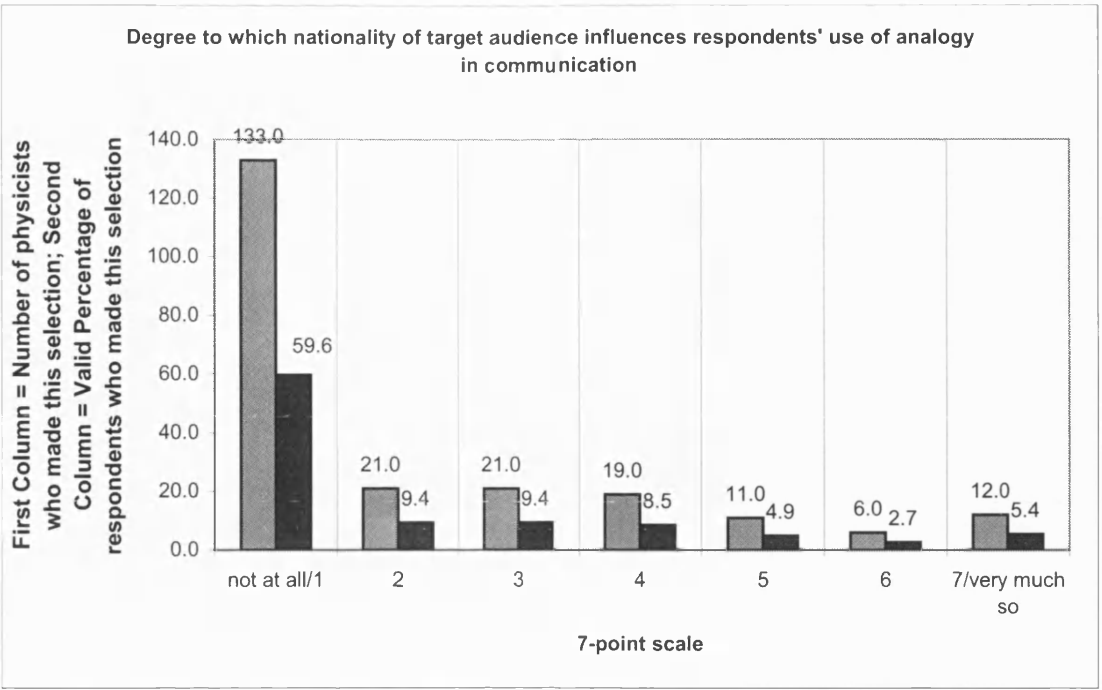

Figure 6.10: Chart showing the degree to which nationality of target audience influences respondents' use of analogy when communicating physics.

As the quantitative data of figure 6.10 suggests, a large majority of respondents indicted that the nationality of target audience did not influence their use of analogy at all. However, analysis of verbal responses revealed a striking variety of opinion. The written responses were re-coded according to certain themes and their frequencies ascertained. They are presented below:

(i)	Nationality is irrelevant	27.1%
(ii)	[Failed to Reply]	24.9%
(iii)	Analogy will only work if it is familiar to the culture of that nationality	18.7%
(iv)	Must avoid colloquialisms and speak slower	11.6%
(v)	Physics is international	6.2%
(vi)	Nationality/language barrier makes analogy more important	3.1%
(vii)	Have no experience of this	2.7%
(viii)	A picture transcends language barriers	0.4%

In their written comments, some respondents echoed the remarks of the physicist from Arizona, saying that the nationality of the target audience may have some influence on their use of analogy. For example, **Phys_190**, (a 44 year old, senior lecturer in physics and astronomy) said, it "can occasionally affect choice of analogy (e.g. famous building as size reference, national currency seen from distance X as small angle reference, sports metaphors). Don't see that it would affect decision to use analogies, unless you are working in a second language."

Similarly, **Phys_35** (a 33 year old post-doc, involved in solid state physics) replied saying: "relating to the audience is important to get their attention. This includes relating to the nationality. Example: do not use references to ice-skating with an Irish audience, since most people have never done it." **Phys_177** (a 24 year old PhD student involved in quantum communication) said that the analogy: "shouldn't be about traffic on the m6 around Birmingham if they're from Tehran."

Respondents who were of the opinion that the nationality of the target audience was a significant factor, (in determining which analogies would be appropriate), *appeared* to have had more experience of communicating with audiences of differing nationalities. They had either recently lectured in a foreign country, had foreign colleagues working with them in their home country, or were foreigners themselves. Below is a selection of key remarks on this issue. (I have underlined key phrases for clarity).

- "Take care to avoid cultural reference; I have recently lectured in Poland." (Phys_216, a 45 year old lecturer involved in quantum information.)

- "You have to remember that some sayings are hard for a non-english speaking person to understand and you could confuse them even more. I have experienced many German speakers who give a literal translation of something that is well known as a saying in German but in English makes no sense at all. The German members of the audience still got it and laughed but we all looked confused." (Phys_51, a 28 year old, radiotherapy physicist / Medical Physicists with the National Health Service)

- "Analogies could be quite difficult with an audience of different nationalities, I have been in seminars where my colleagues from other countries have been lost by the speaker who uses analogies they don't understand." (Phys_83, a 27 year old, PDRA, involved in high intensity laser science)

- "...analogy can be misleading, when a linguistic problem takes past [/part?]. An audience where I know they do not understand every word I am saying would be more grateful with a straightforward approach rather than with a analogon they maybe cannot follow. (Note: I am foreigner myself and know this problem from this point of view ...)" (Phys_77, a 33 year old, PDRS involved in astrophysics)

My case study respondent, Dr. Lawson, also had experience of different nationalities having different approaches. He said to me in his introductory letter of March 2003:

> "In the latter part of my career I attended numerous workshops on emerging concepts and ideas, where there was plenty of controversy and argument; I noted particularly how those with different backgrounds and different nationalities had different ways of thinking about things. (For example 'why does this effect occur?' – 1) 'because the direction of flow has changed' 2) 'because the third term in the equation is now larger than the second' – both true but not necessarily clear to all parties!" [124]

Also, from the 1970s, Dr. Lawson spent some time collaborating with Maryland University, helping with their experiments, and doing theoretical work connected with the experiments. He said he noticed "interesting differences: national differences" during his time abroad. For example, he noted how Japanese physicists usually refrained from asking him questions at group meetings, while their American colleagues hit him with question after question. He got the impression that the Japanese physicists were "scared to say anything" [125] in case they'd make themselves look foolish.

Cultural effects are extremely difficult to unravel. There are at least two other possible factors that may have played a part in the cultural difference that Dr. Lawson noticed. One - Japanese culture places high regard upon the wisdom of elders. These oriental physicists may have regarded Dr. Lawson as an authority figure who should not be challenged through questioning. Two – Japanese culture values/valued a different style of address. The anthropologist Sharon Traweek has written extensively on the cultural differences between Japanese, American and European physicists based upon her observations of the international community of high-energy physicists over a period of thirty years. Regarding differing styles of address, Traweek recounts, how a Japanese physicist once explained to her:

> "the importance in Japan of *harage,* leadership from the force of one's will or, more literally, from one's lower stomach… a good Japanese leader listens and then conveys his position powerfully, but nonverbally. He contrasted this to Americans, who lead from the mouth by talking all the time." (Traweek, 1995, p.213)

Traweek observed a noticeable change in the behaviour of some American physicists who work with Japanese physicists:

> "I have noticed over the five years I have been studying a group led jointly by an American and a Japanese that the American is talking in formal meetings less and less; he is increasingly regarded as a good leader by the Japanese." (ibid.)

[124] Dr. Lawson, in his March 2003 letter to Ciara Muldoon.
[125] Dr. Lawson in conversation with Ciara Muldoon, Jan 2004.

Drawing on Traweek's anthropological studies of high energy physicists and my survey data it seems reasonable to conclude that one should be alert to possible cultural or national differences among one's target audience when doing and presenting physics and one should make every effort to ensure that any analogies used actually 'translate'. Above all, one should try to avoid using slang. This is discussed below.

6.8.1 Using journal article English versus an idiosyncratic vernacular.

In a *Physics World* article of January 2003, Elizabeth Anne (a teacher of English as a foreign language at a French university) identified two distinct versions of the English language. According to Anne: "High English is the sort that appears in research papers, solicitors' letters and other formal settings, while low English is what you speak (and hear) in everyday life and at physics conferences." (Anne, 2003, p.60). Anne urged native English speakers to resist using local 'dialects' when presenting their papers to international audiences, because in her view, physicists whose native language is closer to the Graeco-Roman side of English find it difficult to understand the "earthy Saxon side of the language" (ibid.). As she explained:

> "Talk to any non-native English speaker at a physics conference and they will tell you that while they have no difficulty in understanding German, Italian or French people speaking English, they cannot understand the 'Anglos' themselves. They are so used to reading journal papers written in formal English that they find it difficult to follow the spoken language." (ibid.)

The anthropologist, Sharon Traweek has also highlighted the issue of cross-cultural differences in modes of communication, but from a slightly different perspective. Her ethnographic studies of the international community of high-energy physicists show that Japanese physicists often try to use the same slang as their American colleagues, presumably to be accepted into the 'tribe'. In Traweek's view:

> "It is important to understand that the English of science is American, not British. More specifically I would claim that it is an American lower-middle and working-class men's English, replete with the appropriate slang. I found it amusing to hear some Japanese (and Koreans and Chinese) from rather higher social classes using this idiosyncratic vernacular while giving talks at conferences: certain data points displayed by the overhead projectors onto large screen, for example, were continuously referred to as 'these guys'." (ibid.)

Presumably, this is even more distracting, as both native and non-native English speakers in the audience are respectively amused and bemused by the Japanese speakers' use of such slang. To avoid misunderstandings when presenting ones work to international audiences, the most logical solution would seem to be to use as little slang as possible, and to ensure that any analogies one uses translate across cultural boundaries. Some of the on-line questionnaire respondents were aware of the possible problems, surrounding physicists' use of journal article English versus colloquial English. They may well have remembered reading Anne's Physics World article, which had appeared two months previously.

For instance, **Phys_ 54** (a 40 year old lecturer in theoretical physics) said: "I have heard it said that non-English speakers have a hard time understanding talks at conferences because native English speakers like myself use formal scientific language in written work, but colloquial English in spoken addresses, which for them is difficult. Although I am aware of this problem, when I get going in a lecture, I suspect I am just as bad as any other native English speaker. Habits like that are hard to break." **Phys_9** (a 32 year old lecturer in physics and astronomy) said: "analogies which rely on slang, gestures or particular social concepts may fall flat or even cause offence in other countries." **Phys_27** (a 25 year old PhD student involved in nanophysics applications) noted that: "Non-native english speakers often just have research paper english, which is different to the more colloquial phrases normally used in making an analogy."

These findings on the degree to which nationality affects physicists' use of analogy when communicating with different audiences gave rise to several hypotheses regarding my sample of questionnaire respondents. Perhaps one or more of the following factors played a part in the data retrieved:

(a) Many are native English speakers and have had little experience of being lectured to in another language;

(b) Many have had little experience of communicating with an international (non-native-English speaking) audience, in particular, of giving lectures/public talks outside of the UK, Ireland, the USA, Canada, Australia, New Zealand, etc.

(c) Many are experienced at communicating with international audiences but it is their opinion that their use of analogy is in no way influenced by the nationality of their target audience;

(d) Many interpreted the term "analogy" to mean formal, mathematical analogy. Consequently the nationality of the audience does not influence their use of abstract analogies which are devoid of geographical, cultural, monetary, sporting references.

An attempt was made to clarify this issue in follow-up e-mails with a select sample of respondents. Several questionnaire respondents who said that nationality had little or no affect on their use of analogy were asked the following question:

> *Q. Have you had much experience of giving a lecture or talk to an audience comprising different nationalities (who were not native-English speakers) or giving a talk on foreign soil where sporting, geographical, monetary or iconographic analogies might need to be adapted to suit the audience's background?*

Respondents were then supplied with some of the comments of respondents who said nationality did affect their use of analogy. For example, Phys_216's remark: "Take care to avoid cultural reference; <u>I have recently lectured in Poland."</u>

I received only one reply: from **Phys_185,** a 45 year old, female, research fellow, whose research interests include: "Quantum computing, quantum many body physics, phase transitions, physics of information."

In her original reply to the on-line questionnaire, **Phys_185** had said that she rarely (i.e. <u>3</u>/7) uses analogy in her research and very rarely (i.e. <u>2</u>/7) generates original analogies. You may recall I quoted her in section 5.1 as saying: "What I use is often stronger than analogies, in that the underlying mathematical description is the same or similar in the first approximation. For example, harmonic waves appear all over the place in very different physical situations."

She also indicated that she rarely (i.e. <u>3</u>/7) uses analogy when communicating with experts or intermediates and very rarely (i.e. <u>2</u>/7) uses analogy when communicating with novices. However, I reasoned that this might be because she very rarely (i.e. <u>2</u>/7) communicates physics with the general public and rarely (i.e. <u>3</u>/7) with undergraduates.

Also, when responding initially to the on-line questionnaire, **Phys_185** indicated in that her use of analogy was somewhat (i.e. <u>4</u>/7) influenced by the *"physics expertise"* of the target audience but "not at all" by the *"prestige of occasion"* or *"nationality"* of her target audience.

In response to my follow-up e-mail seeking clarification, **Phys_185** said:

> "I have given plenty of talks to multi-national audiences, in other countries, etc.. Also, a significant fraction of my colleagues are from other countries. First, I think I interpreted 'analogy' more narrowly than you intended: of course I try not to use slang in my talks. I have a fairly standard accent so (unlike my Glaswegian colleagues) I am reasonably easy for non-native speakers to understand. Having lived in other countries myself and travelled fairly widely, I'm used to communicating with non-native English speakers so probably I adapt without thinking consciously about it. I adapt to native English speakers from different regions of the UK too, I don't think I make a special effort for some non-native nationalities. I think I try to be clear to all audiences, and I have enough experience of how to do it (through conversation, where feedback on whether someone understood is immediate) that I don't need to think about it in advance, or in relation to specific cultures. Well-designed presentations also help, if the key words and concepts are available in words and pictures, the spoken words are easier to follow. I cannot think of any examples like your other respondents, either from my own talks or other people's. I can think of many examples of misunderstandings from ordinary conversation, just not from talks. Perhaps in my field we don't use analogy very much to get our ideas across!
> The complaints people make about talks that are hard to understand are usually that the speaker mumbles, or speaks too fast: these can happen with native and non-native speakers alike, and are much more common than problems with the vocabulary used. The next most common complaint about native speakers is their accent, especially if not from the UK or US (New Zealand and Glaswegian are top of the incomprehensible list)."

Several interesting issues arise from **Phys_185's** remarks. First, that she interpreted analogy "more narrowly" than I intended. This supports my earlier contentions that many respondents interpreted analogy more narrowly than intended resulting in their apparent wariness of using analogy in their research or when communicating in formal settings with experts. Second, that we often sub-consciously and spontaneously adapt the style and content of our speech, upon receiving immediate feedback from our audience. In Bakhtin's terminology this is the unconscious 'addressivity' of our 'utterances'. Third, that in her experience, audiences have more problems with speakers' unclear diction than with the vocabulary they use (including the vocabulary used in drawing analogies). Fourth, that perhaps researchers in her field ("Quantum computing, quantum many body physics, phase transitions, physics of information") don't use analogy very much to get their ideas across. There were some patterns in the data to suggest that certain branches of physics made more use of analogy – perhaps because journals in those areas were more open to the inclusion of analogy as a legitimate problem solving tool. I believe that this issue should be pursued in future studies.

6.9 Conclusions:

6.9.1 Can analogical reasoning provide insights when conceptualising and communicating physics?

Yes. Analogies offer insights to experts, intermediates and novices, but they are usually different types of insights. The insights novices get through analogy are usually surface level insights. They associate a topic from physics with something from their experiences in every-day life. Thus, for example, they learn that: "A Tokamak is like a donut, but filled with plasma instead of cream." (Phys_189). This is an example of analogy used in the context of set **A** of my venn diagram in section 5.5. Novices can use this visual analogy as a framework around which to build a better understanding of accelerator physics should they wish to do so at a later date. Intermediates tend to do just that, extending and deepening their understanding of the physics concept they are dealing with. Thus, they use analogies in the context of sets **A** and **B** of my venn diagram. Experts on the other hand, have a broader range of insights. They have the same 'associative insights' that novices and intermediates have, but they also have deeper insights that are the result of the mathematical and geometrical intuitions they have acquired through studying the underlying physics in considerable depth. Their insights go beyond comparing a concept from physics with something from everyday life of popular culture, their insights also often involve comparing the underlying mathematical structure of one physical situation with that of another. Thus, their insights can involve physical and pictorial components but can also be highly abstracted and related to mathematical formalism. This context fits into set **C** and the intersection of sets **B** and **C** in my venn diagram. In chapters 7 and 8, we will see how one particular physicist-engineer used good analogies throughout his career (from the 1940s to the 1980s) as a means of acquiring physical and pictorial insights for himself and providing insights to his colleagues.

6.9.2 What are the features of good analogies?

From my analysis of the data presented in chapters 5 & 6 I can suggest that good analogies tend to have the following features. Good analogies that appear in set **C** of my venn diagram in section 5.5 are useful heuristics (i.e. rules of thumb) in problem solving and generative (i.e. suggesting new avenues to pursue through more rigorous analytical means). Good analogies that appear in the sets **C** and **B** of my venn diagram hold for a hierarchy of relations (from the mathematical equations governing the system to the physical and pictorial expression of system features) and are useful tools when exploring a new domain or explaining a new concept to a colleague. Good analogies that appear in sets **B** and **A**, are easy to express (pictorially, verbally, symbolically) and are useful in different contexts (formal & informal settings; with experts, intermediates & novices). Analogies which span all three sets, **A, B** and **C** are usually easy to express, memorable, amusing, and are often those whose origins can be traced back to eminent physicists. The same analogous idea can be used in different ways in different contexts. For example, as discussed in section 5.6.1, an analogous visualisation of loops and weaves is used by Rovelli (2003) to help **Physics World** readers conceptualise these highly abstract entities. However, at a conference of experts, Rovelli (2001) uses a humorous sketch of loops being woven into a jumper to highlight the fact that the analogous visualisation should not be taken too literally. Thus, the composition of the target audience can greatly influence the type of analogy used.

6.9.3 What are the key factors which influence respondents use of analogy when communicating with different audiences?

On the next page table 5.2 summarises the forms of analogy employed in different contexts. I presented this table in the previous chapter when dealing with the forms of analogies used by respondents in their research. However, at that point, I had not presented my questionnaire data on the key factors that influence respondents' use of analogy when communicating with different audiences. Having now presented this data, I can conclude that the ***physics expertise of the target audience*** and, to a lesser extent, the *tone of discussion* are the most significant factors. The nationality of the target audience was influential for a minority of respondents.

Even though their target audience may have considerable expertise, when the context is **informal** and physicists are creatively playing with ideas in a relaxed setting, a much broader range of analogies are used. This ranges from analogies having well-established, underlying mathematical structure, to simple, playful analogies which break down if taken beyond surface similarity. When the context is more **formal**, physicists tend to avoid the playful analogies, employing only analogies with a well-established underlying mathematical structure - - what **Phys_127** termed, "rock solid analogies." Avoidance of analogy in formal settings is more common amongst **young** physicists who wish to be taken seriously by their peers and superiors, and consequently adopt a formal, dignified tone. Those who have already established themselves as noteworthy physicists can afford to be more flippant in formal settings because they have nothing to prove. However, with a high-ranking position comes a responsibility not to mislead their audience by using overly simplistic analogies.

Thus, respondents will either use <u>fewer analogies</u> or <u>more complex analogies</u> as their audience's **physics expertise** increases, because they do not wish to present an over-simplified view to those with considerable expertise. As a consequence, it is those who are least able to evaluate the merits of an analogy that are most likely to have analogy used on them. However, the group most at risk of misunderstanding analogies, adopting a naïve interpretation of analogies or failing to see the limits of analogies are secondary and tertiary level students. These intermediates are encouraged to use simplified models and analogies on a regular basis in their formal education in order to solve specified problems. Once assimilated, the models and analogies become part of their conceptual toolkit. As a result of their practicality they are taken by many to be realistic, 'for all intents and purposes', and may even cease to be regarded as 'analogies'. We know from Spiro et al's (1989) research that even when the **disanalogies** are made explicit to medical students, many still hold erroneous assumptions, misled by connotations of non-technical descriptive language.

I believe that these findings will be of interest to practicing physicists interested in the forms of analogies used by their peers to conceptualise and communicate physics in different contexts and may also be of practical use to science educators. For example, my identification of the features of good analogies could be used in future research projects to devise a searchable databank of good analogies. This would will involve collaboration between practicing physicists with a flair for communicating with different audiences; science educators who have experience of students' differing learning styles; and researchers like myself, who approach the area through the lenses of history, philosophy and psychology of science. Such a resource could then be used to train science students to use conceptualisation techniques similar to those used by practicing physicists – in particular, the use of playful analogies, structured so that they hold for a hierarchy of relations but are generative and expressed physically, pictorially and mathematically.

Expressed As	Set A: Verbal or Physical or Pictorial Analogies	Set B: Physical and Pictorial Analogies	Set C: Formal, Mathematical Analogies
Systematicity	Low	Medium to High	High
Definition	The analogies are often novel and amusing, relating abstract physics concepts to familiar, everyday things like dazed chickens, cheese sandwiches, Snickers bars, football stadiums, donuts, etc.	The physical picture attached to one situation can be used to visualise another. These idealised pictures are usually used iteratively: further refined and abstracted through rigorous mathematical and experimental testing.	The same mathematics can be used to describe two situations. Phenomena in one situation will have a counterpart in the second, as the mathematics for the two is identical.
Example	"A Tokamak is like a donut, but filled with plasma instead of cream." Phys_189 "Reversal of magnetisation through a magnetic logic NOT-gate likened to a car performing a three-point turn." Phys_191	"Cerenkov light is created when a particle passes through matter at above the local speed of light. The effect is similar to the shock wave created by an airplane flying at above the speed of sound." Phys_198	"I quite often use the analogy of cold atoms to try to tackle problems in other areas. Cold atoms are a very clean and well understood research topic where I have experience in, and its results are widely applicable also to other areas." Phys_35
Often rely on	Popular associations; Creative imagination;	Geometrical intuition Kinaesthetic awareness (of macroscopic capacities); Tacit knowledge (gained through experimentation);	Geometrical intuition (seeing patterns and symmetries in the underlying mathematics)
Functions **(Epistemological Aims)**	Tools of Explanation. To make physics accessible, memorable and entertaining, in order to enlist support. Occasionally used by expert physicists in private conceptualisation to play with ideas.	Tools of Exploration; Provide physical and pictorial insight; Mechanisms underlying phenomena in analogous systems can be compared & contrasted.	Tools of Exploration; Allow direct comparison of physical systems to be made on an abstract mathematical level. Basis for computer simulations;
Contexts of Use	(1) Private Conceptualisation;	(1) Private Conceptualisation;	(1) Private Conceptualisation;
	(2) Expert-Expert Communication in **very informal** settings; Often used to entertain an audience of experts or to make a point in a lively debate amongst peers;	(2) Expert-Expert Communication in **formal & informal** settings; Use in journal publications is dependent on norms of research area and "in-house style" of journal. Some journals object to creative use of language.	(2) Expert-Expert Communication in **formal & informal** settings, including journal publications & presentations to conferences of experts;
	(3) Expert-Intermediate Communication in **informal** settings (used to entertain and offer insights);	(3) Expert-Intermediate Communication in **formal** and **informal** settings;	(3) Expert-Intermediate Communication in **formal** and **informal** settings;
	(4) Expert to novice communication (to make physics accessible and memorable by drawing on concepts from everyday life);	(4) Expert to novice communication (in particular to visualise the unseen, e.g. atomic physics, nano-physics, cosmology and astrophysics,etc.);	(4) Almost never used by physicists to communicate with novices as concepts from the source domain would be unfamiliar to novices.

Table 5.2: Summary of Different Forms of Analogy Employed in Different Contexts.

Chapter 7:

An Outline of Dr. Lawson's Research Background

Figure 7.1: Image of Dr. John Lawson speaking at the *Symposium on Heavy Ion Fusion* at Darmstadt in 1982. (This photo, courtesy of CERN, appeared in the RAL Bulletin no. 5, on 6th April, 1988, announcing Dr. Lawson's election as a Fellow of the Royal Society).

"Widely in demand as a consultant, lecturer and writer, his book, 'Physics of Charged Particle Beams' is a classic and the phrase 'talk to John Lawson' has become a by-word amongst accelerator designers and fusion practitioners." [126]

[126] An excerpt from the Rutherford Appleton Laboratory Bulletin, (02-November-1987) reporting on the occasion of Dr. Lawson's retirement from the RAL.

7.0 Overview:

In this chapter I profile Dr. Lawson, an engineer-physicist who frequently took on the role of 'translator' at physics-engineering workshops and conferences in the 1960s, 70s and 80s. The data stem from a content analysis of 35 of his scientific papers (1946-1997), his book on the physics of charged particle beams (1988, 2nd edition), and personal correspondence and semi-structured interviews that we carried out sporadically between 2003 and 2005 (face-to-face and over the telephone).

Although the conceptualisation and communication techniques used by Dr. Lawson may be indicative of his cognitive style I must emphasise that my aim was not to explain how he developed his cognitive style. Feist and Gorman's (1998) Structural Equation Model provided a useful theoretical framework and graphical means of highlighting the different spheres of influence, but I did not use it to uncover statistically significant relations between the biological, developmental, cognitive or social spheres. In general, directional influence between personality and scientific behaviour remains an open question (cf. Eiduson, 1974; Feist, 1993; Feist & Gorman, 1998). As Barwise & Etchemendy (1996, p.180) remark, efficient reasoning is almost certainly "inescapably heterogeneous (or 'hybrid') in nature." Enforcing artificial compartmentalisations in an attempt to analyse it, usually leads to erroneous conclusions. However, in the course of our interviews, Dr. Lawson frequently mentioned experiences that he believed shaped his way of thinking, such as his work habits.

Thus, in this chapter I have provided some background information on Dr. Lawson's education, training, working environment and research interests in order to gain a better understanding of the contexts in which he found certain conceptualisation and communication tools useful. As discussed in section 2.4.6, a cognitive styles framework was used to guide these investigations. It was used to frame questions concerning his ability to act as a translator or synthesiser of ideas between sub-branches of physics and engineering for example. As can be seen in this chapter and the next, this methodological approach proved quite successful and helped to uncover many interesting results. Thus, in this chapter I explore Dr. Lawson's training, research background and working environment. I mention his role as a 'synthesiser' and 'translator' of ideas between sub-disciplines in his field. In chapter 8 I discuss his use of analogy and synthesis to acquire and promote insights when conceptualising & communicating physics to experts and intermediates, drawing on examples from his scientific papers and book.

7.1 Chronological outline of Dr. Lawson's career.

A chronological outline of Dr. Lawson's career is provided in appendix 7, section A7.1. From this we can see that John Lawson graduated from Cambridge in 1943 with a degree in mechanical sciences, which included electrical engineering and radio, as a preparation for radiolocation (radar) research.

Immediately after graduation he started his career at the Telecommunications Research Establishment (TRE) Malvern: Micro Wave Aerials Group, where he worked on airborne radar. Four years later (in 1947) he joined the Atomic Energy Research Establishment (AERE) Malvern Branch: Accelerator group. Four years after that he transferred to AERE Harwell: General Physics Division.[127] At Harwell he lead the team developing the X-band Klystron. In 1952 he and his colleagues made an important theoretical contribution to accelerator theory by his identification of resonances in strong focussing synchrotrons. In 1955 he turned his attention to fusion power and two years later derived the 'Lawson Criterion' which relates to the conditions needed for a fusion reactor to reach ignition.

He joined the Rutherford Appleton Laboratory (RAL) in 1961 and eight years later received his Sc.D. Physics (also at Cambridge). In 1985 he received the **Thomas Young Medal** from the Physical Society, given for Optics. He retired from the RAL in 1987. Paul Williams, RAL director at the time, said on the occasion of Dr. Lawson's retirement that: "To say he will be missed is the understatement of the year… We have learned to trust and respect his council and, so that we do not lose touch, have invited him to become one of the RAL's Honourary Scientists." (RAL Bulletin, 02-Nov-1987).

His book, *The Physics of Charged Particle Beams* was first published in 1977. The 2nd edition, with some clarifications, was published in 1988. In the same year he was elected a Fellow of the Royal Society (FRS). An RAL bulletin announcing his election as an FRS emphasised the usefulness of his book, *The Physics of Charged Particle Beams*, describing it as a, "study in depth of problems of high intensity beams with the objective of integrating material from widely scattered fields (microwave tubes, electron optics, accelerators, plasma physics etc.) and providing a general unified treatment." (RAL bulletin, 06-04-1988). The same bulletin remarked that the book "has since had numerous reprints and been translated into Russian and, perhaps the ultimate accolade, into Chinese!"

Dr. Lawson has close to 100 formal journal publications including: Journal of the Institute of Electrical Engineers; Nature; Philosophical Magazine; British Journal of Applied Physics; Nucleonics; Journal of Electronics and Control; Journal of Nuclear

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[127] now HQ of the United Kingdom Atomic Energy Authority (UKAEA)

Energy; Radio and Electrical Engineering; Nuclear Instruments & Methods in Physics; American Journal of Physics; Journal of Scientific Instruments; IEEE Transactions on Nuclear Science; Physics Letters; Particle Accelerators; Contemporary Physics; Physics of Fluids; Plasma Physics; Advanced Electronics and Electron Physics; Annual Review of Nuclear Science; European Journal of Physics; Plasma Physics and Controlled Fusion;
Having provided this overview of John Lawson's career I will now discuss some key factors which will help us understand the contexts in which he came to find certain conceptualisation and communication techniques useful.

7.2 Key factors which may shed light on Dr. Lawson's style of thinking.

7.2.1 His early childhood experiences:

During our telephone conversation of 22-03-2004, Dr. Lawson recounted how as a boy he was "always doing experiments and building things" [e.g. a simple galvanometer to measure electric current]. He said these experiences: "partly formed my ability to do things in an economical way, because I never had any money - - I mean it was a question of trying to scrounge things or adapt them." (ibid.). It is worth noting that experimental tinkering during childhood is a common feature in historical case studies of scientists, e.g. Faraday, Edison, Bardeen, Krebs, Feynman and Maxwell. My intention is not to place Dr. Lawson on a pedestal alongside revolutionary or Nobel prize-winning scientists, however as most case studies are of exceptionally gifted scientists one cannot but compare and contrast with the greats. In their biography, Hoddeson & Daitch tell how John Bardeen[128] displayed a flair for experimental work during his childhood years in the 1920s. Captivated by the magic of radio, "John built his own crystal set and receiver, 'from dime store wires, oatmeal boxes, little straw suitcases and the crystals.' Carefully winding copper wire around an oatmeal box, he made a tuning coil." (Hoddeson & Daitch, 2001, p.20-21). Similarly, Larry Holmes, in his two volume biography of Hans Krebs,[129] notes that when Krebs:

> "was about ten years old, he constructed, out of cardboard and paper, an elaborate device in which a marble placed at one end would roll through a trough, following a

[128] Bardeen shared the Nobel Prize in Physics in 1956 with Shockley & Brattain, "for their researches on semiconductors and their discovery of the transistor effect," and in 1972 with Cooper and Schreiffer, "for their jointly developed theory of superconductivity, usually called the BCS-theory".
[129] In 1953 Krebs shared the Nobel Prize in Physiology or Medicine with Fritz Albert Lipmann. Krebs received the award "for his discovery of the citric acid cycle," Lipmann "for his discovery of co-enzyme A and its importance for intermediary metabolism"

> pathway that went downward and upward, around curves and through spirals, without stopping or overshooting. Called the 'coo coo bahn,' Hans's invention made a great impression on the family and on others who saw it." (Holmes, 1991, vol 1, p.47).

Dr. Lawson told me during a telephone conversation (13-01-2005) that he has always had "a wide curiosity" adding, "I liked to know about everything." [130] According to the renowned scientist Peter Medawar, capable scientists have a strong desire to comprehend – a trait he calls "exploratory impulsion." (Medawar, 1979, p.7). The above examples are intended to show that curiosity, inventiveness and experimental and manipulative skills are characteristics shared by many scientists and engineers, including Dr. Lawson.

7.2.2 His formal education:

Dr. Lawson started out in Classics but changed tracks midway, emerging from Cambridge in 1943 with an unconventional 'wartime' degree in mechanical sciences (with a strong engineering component). He believed that his somewhat unorthodox formal education was a key factor in the conceptualisation and communication techniques he used in his career. For example, in a written response a my follow-up questionnaire he said (04-Oct-2004):

> "I did not have a degree in physics. All my formal university training was two years of an electrical engineering degree in wartime. Most of my physics was self-taught, and is full of short-cuts and unorthodox analogy type connections. By going a strange route I often arrived before those that worked in a more formal and orthodox way."

Going a strange route, often involved using analogical reasoning. Dr. Lawson made this point in his introductory letter to me saying:

> "my thought patterns were rather different from those of colleagues with a conventional physics degree, and looking back at my occasional educational papers I realised how many of them are on analogies. The response to them was varied: some found them interesting, others not at all, though they often formed popular conference papers." (Lawson, in his first letter to me in March 2003).

Dr. Lawson's use of analogy could be paralleled with that of Einstein and Faraday. This is discussed further in subsequent sections of this chapter and especially sections 8.4 & 8.5 of the next chapter.

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[130] During our Jan 2004 interview at his residence, Dr. Lawson said his son showed a similar interest in building things, saying: "Actually my son also used to do this sort of thing, and he, using *Mechano*, he made a machine to follow a white line and that sort of thing - - Which was the sort of thing that I enjoyed doing."

7.2.3 His working environment during his formative years:

Detailed accounts from the history of science attest to the importance of working and learning environment in the development of methodological practices. For example, as Nersessian points out, Maxwell's training as a mathematical physicist, skilled in continuum mechanics, "shaped the nature of the theoretical, experimental, and mathematical knowledge and the methodological practices with which he formulated the problem and approached its solution." (Nersessian, 1995, p.212). Maxwell was also fortunate in being able to draw upon remarkable intellectual resources in the form of Michael Faraday and William Thompson. This is in contrast to continental physicists working on electromagnetism at the same time who, as Nersessian points out, "employed quite different practices and drew from fundamentally different mathematical and physical representational structures." (ibid.). Again, my aim is not to imply that Dr. Lawson and Maxwell were similar – they differed in many ways, most notably in their formal physics training. My aim is to highlight that working environment has been shown by historians of science to be an influential factor in shaping methodological practices.

Dr. Lawson's apprenticeship at the Telecommunications Research Establishment (TRE) Malvern (1943-1951) was a particularly formative time in his career. Having had no physics education at college and little relevant maths Dr. Lawson learned what he needed 'on the job', working in an environment "surrounded by some of the best physicists in the country." [131] Malvern had a staff of 2000 in 1942 and over 3500 after the war. According to Dr. Lawson, Malvern was in some ways like a university, with frequent meetings, workshops and lectures given by "really top people from universities who had been sent to Malvern." [132] Many of these scientists were involved in the development of microwave radar during world war two, e.g. A.C.B. Lovell and H.W.B. Skinner. The practical component of Dr. Lawson's work at Malvern was of paramount importance. Dr. Lawson's workspace was compact: he had about 6 feet of bench space for himself in a laboratory with 6 other English men.[133] Dr. Lawson's close-knit environment, characteristic of Malvern, was particularly influential to his progress as an engineer-physicist. It enabled him to bounce ideas off his colleagues and hone his tacit skills at building equipment. The value of collaborative exchanges, teamwork and 'synergism' is emphasised by Medawar,

[131] Dr. Lawson, in his March 2003 letter to me.
[132] Dr. Lawson during our telephone conversation of 13-01-2005
[133] During our telephone conversation of 13-01-2005, Dr. Lawson explained that they had: "all sorts of backgrounds. Mainly youngish people, many of them had come in straight from university like me and had some experience which was relevant in radio or something of that sort. They started off everybody by 6 weeks of an induction course, given by the staff. These were very good. And they really did give you quite a lot of information."

in his *Advice to a Young Scientists* (Medawar, 1979, p.7). Travis, in his studies of the development of microwave radar in Britain and Germany during WWII, makes a similar point, noting that:

> "the successful [radar development] teams (in terms of quick problem solving) had very strong common bonds and worked together in small spaces. This appears to have provided the optimum conditions for sharing embodied knowledge in the form of practical skills and also in terms of ideas about how to progress. These ideas were usually generated by having an intimate knowledge of the apparatus. The ability to consult quickly with colleagues who shared this knowledge, or possessed greater knowledge, facilitated quick progress." (Travis,1995, p.87)

It was here, at Malvern, that Dr. Lawson first learned **the value of informality when communicating science**. For example, Dr. Lawson recounted how very senior RAF people who wanted to see something would come into the lab and, "chat without going through all this formality of senior officer grades and this kind of thing." [134] This made it easier to transfer ideas from person to person because, "the people in the lab could immediately see what the other operational people wanted." (ibid.). Dr. Lawson said, "It crossed barriers both on subject and on seniority which was, I think, particularly British - - and probably American as well." (ibid.). Dr. Lawson contrasted the informal Anglo-American approach with the formal (highly regulated) approach of the German scientists and military during the war, saying it may have been a key factor in the outcome of the war. Supporting evidence for Dr. Lawson's remarks can be found in Travis (1995) and in *Radar Recollections*, an on-line archive compiled by the University of Bournemouth's Oral History Unit in collaboration with The Centre for the History of Defence Electronics (CHiDE). From the latter course, we read that:

> "Whilst at Worth [the TRE base prior to moving to Malvern] in 1940, A.P. Rowe [Chief Superintendent of TRE with overall control of all the research projects in hand] conceived the idea of inviting senior military personnel to visit TRE on Sundays to meet with the rest of the research engineers and scientists working in the team. These gatherings were very informal and even the most junior staff were encouraged to contribute their ideas. If an idea was put forward that had merit, it could be adopted there and then because all the main decision-makers would be there. Such informality (and trust) at such a powerful level was unprecedented. A great sense of purpose was thus built up between the researchers and the military decision-makers." [135]

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[134] Dr. Lawson during our telephone conversation of 13-01-2005

[135] Source: http://histru.bournemouth.ac.uk/Oral_History/Talking_About_Technology/radar_research/ Accessed: 25-09-2005

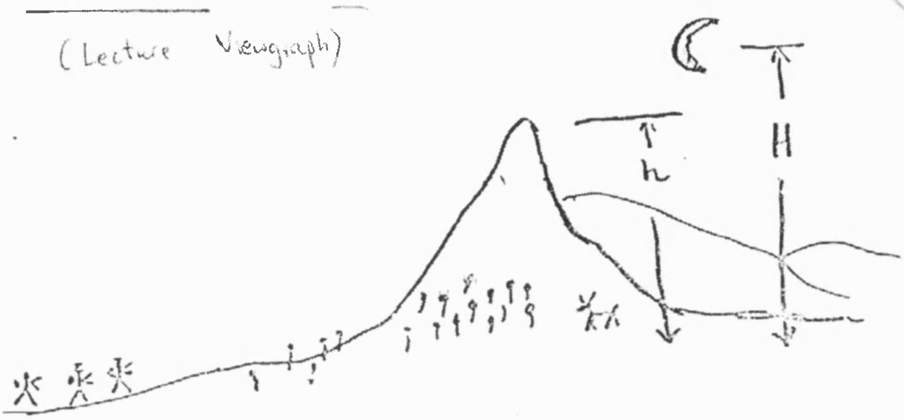
As discussed in chapters 5 and 6, mathematical, physical and pictorial analogies are often employed in informal exchanges between experts. Such analogies rarely make it into published accounts, unless the scientist is (i) an enthusiast for analogy, (i) convinced it can provide useful insights to many readers, (iii) is well regarded by his peers. As discussed in the next chapter, Dr. Lawson employed analogy to its fullest potential as a means of bridging 'linguistic divides' between sub-disciplines and providing his colleagues with valuable insights. I would argue that Dr. Lawson's 'unorthodox' formal education and informal, close-knit working environment during his formative years played an important part in encouraging his propensity to reason and communicate via mathematical, physical and pictorial analogies.

7.2.4 A "slightly traumatic" event which occurred during Dr. Lawson's first project.
When Dr. Lawson was in his early 20s he began work on the construction of an electron model of a frequency modulated cyclotron. In order to get going on the project he ordered the most expensive part which was going to take a long time to arrive. This would seem like a logical course of action in order to make the best use of the time and funding available. In fact Dr. Lawson may have learned this approach from his early childhood experiences – scrounging parts to build home-made instruments. However, by the time the mechanical part arrived (and the project was under way) Dr. Lawson realised that he had, "missed out a lot of other things, and the whole thing collapsed." He said it was, "slightly traumatic - - I suppose I was in my early 20s - - but that was something which of course I always remembered {gentle laugh}. It was a teaching - - a learning experience." [136] The psychologist and historian of science, Howard Gruber would call this "slightly traumatic experience" an '*affective transformation*', because it affected the 'network of enterprise' (Gruber, 1980, p.292) which Dr. Lawson subsequently developed. Firstly, it shaped Dr. Lawson's approach to subsequent projects. For example, in the latter part of his career, Dr. Lawson became renowned for his ability to "assess new concepts which people put forward" (ibid.), and by his own (modest) estimation was, "a good critic, really." (ibid) Secondly, it became part of his teaching repertoire. For example Dr. Lawson used the humorous sketch (figure 7.2 on the next page) to highlight the dangers of beginning a project with insufficient analysis. I believe that this 'slightly traumatic experience' must be taken into account if we are to understand the network of enterprise which Dr. Lawson subsequently pursued. This is discussed further in 7.2.5 and 7.2.6.

[136] Dr. Lawson, during our telephone conversation of 22-March-2004

A Fable 1982

(Lecture Viewgraph)



Project - To reach the moon.

The moon is high, therefore to reach it we must go upwards. The obvious way up is to climb a mountain.

We organized an expedition. Half way up the mountain we started thinking, and realized that there was a necessary but not sufficient criterion for success.

$$h \geq H \quad (1)$$

Some simple surveying showed that this cannot be met, so we came down and built a rocket. (On the way down we found a gold mine. That was quite unexpected).

JDL

Figure 7.2: A sketch supplied by Dr. Lawson, in his March 2003 letter to Ciara Muldoon. Post-it note annotation reads: *"A useful analogy for people who start projects without adequate analysis to see whether there are any fundamental snags. (Engineers are more cautious)."*

7.2.5 His Personality:

In our first interview, Dr. Lawson said he was: "rather a timid person… a bit of a 'loner' really. And also I was a bit of a 'loner' in my research." [137] There is considerable evidence to suggest that scientists tend to be more independent, introverted and less sociable than non-scientists (cf. Feist and Gorman, 1998). This is especially true of creative scientists, although creative scientists are apparently more open and flexible in thought or behaviour (ibid.). However, considerable uncertainty surrounds the directional influence between personality and scientific behaviour. As Feist and Gorman say: "to put it simply, do smart, conscientious, introverted, driven, and controlled people become scientists or does science create smart, conscientious, introverted, driven and controlled people?" (Feist & Gorman,1998, p. 29). Most probably, there is a mutual influence.

In our third interview, when asked if the freedom to wander through many branches of physics was part of his job or as a result of having an interest in something, Dr. Lawson said: "I had an interest." But suggested that his explorations in other branches of physics also suited his employers, adding: "I was better working on my own rather than as a team member, so I was just allowed to do what I wanted to." [138] As mentioned in section 7.1, Dr. Lawson has close to 100 formal journal publications. His independence is reflected in his published work: he is the sole author of a large fraction of his publications. He remarked upon this, saying, "compared with most scientists I think that...a bigger fraction of my work has got just my name on it." [139] Larry Holmes' comments concerning scientists who move to new areas of expertise may be relevant here. Holmes remarks that,

> "If the skills and experience a scientist accumulates while following an investigative pathway become his 'personal knowledge,' then to switch to another pathway requires more than a different set of experiences. In some deeper sense it involves a new personal identity." (Holmes, 2004, p.xix)

Holmes point may shed some light on Dr. Lawson's tendency to work independently. A timid individual is unlikely to attempt to become fully assimilated into a new community of practice without first working independently to bring themselves 'up to speed' on the conventions, techniques and viewpoints of the new community they are engaging with.

[137] Dr. Lawson during, our first interview at his residence, 15-01-2004
[138] Dr. Lawson during our telephone conversation of 13-01-2005
[139] Dr. Lawson during our telephone conversation of 13-01-2005

7.2.6 luck. On the occasion of his retirement from the RAL, Dr. Lawson said that luck had played a large part in this success as a scientist. The RAL bulletin from that occasion reads:

> "John thanked everyone for the gift (an elegant wrist-watch) and for the good wishes expressed. He believed that luck played a large part in life. It certainly had for him. He had, he said been lucky in being in the right place at the right time and in the people he had worked with and for. On the whole, his career had been a happy one. 'This has been a wonderful occasion. Thank you all for coming,' he said." (RAL Bulletin 02-22-1987)

Dr. Lawson's words are reminiscent of those of the late John Bardeen, recipient of two Nobel prizes in physics. As Hoddeson & Daitch tell us in their biography of Bardeen, he:

> "himself claimed that 'accomplishments are a good bit of luck – being in the right place at the right time – and having the right associates.' He considered himself 'lucky' to have been 'on the ground floor of solid-state physics.' But serendipity cannot explain why Bardeen so *often* found himself in the right place at the right time to support his creativity." (Hoddelson, L. & Daitch, 2002, p.328)

The same could be said of Dr. Lawson. As Louis Pasteur famously remarked, fortune favours the prepared mind.

7.2.7 Working environment in later years - the freedom to pursue his own research interests:

The important connection between scientific innovation and freedom to carry out independent research is highlighted by Rappa & Debackere (1993). Larry Holmes remarks that:

> "some individuals 'drift' or 'migrate' across speciality boundaries or 'diversify' into more than one area, but unless scientists are forced to change because of policies imposed by the organization within which they work, such movements are typically quite gradual transitions rather than abrupt shifts." (Holmes, 2004, pp. xv-vxi).

In fact according to John Ziman, "Given the freedom to do so, the natural tendency of most scientists is to concentrate for years on a few problems in a narrow area of research." (Ziman, 1987, pp.18). Dr. Lawson acknowledges the key role these institutions played in guiding his career path, saying:

> "I've been fortunate in having a job where I worked on all sorts of different things, and I've also been in an atmosphere which doesn't exist so much now of freedom and not too much constraints on money and being able to do what one wants." [140]

[140] Dr. Lawson, during our telephone conversation of 22-March-2004

He also noted that, "Funding was not a consideration during the war. You had as much money as you wanted." [141] Such freedom and independence is rare in the current research climate. As Brad Wray notes, "Now that 'big science' is the norm in many fields, young scientists who have access to the equipment required to make significant discoveries are usually working under someone else's direction." (Wray, 2003, p.146).

Dr. Lawson was afforded the opportunity (in fact, encouraged) to 'migrate' or 'drift' into new research areas first at Harwell (1951-1961) and then, even more so, at the Rutherford Appleton Laboratory (1961-1987). There he worked free-lance, following what seemed to him to be the most interesting developments. As a result, Dr. Lawson gained experience in at least five sub-fields of physics during his career. He was heavily involved in Applied Optics (his work on particle beams included a lot of optics, and in 1985 he was awarded the Thomas Young Medal from the Physical Society, given for Optics); Nuclear Physics, Plasma Physics and High Energy Particle Physics (through his work on accelerators), and was also, though to a lesser extent, involved in Astrophysics, (when he spent some time exploring the possible parallels between cosmic radiation and plasma physics & beams, where he became well acquainted with the legendary Dennis Sciama.[142] Dr. Lawson acted as team leader on several projects at Harwell. Both at Harwell and the RAL workers were encouraged to disperse, re-educate themselves and remain at the cutting edge of research for the benefit of the institutions. Dr. Lawson told me:

> "... we had a good group [at Harwell]. The question was often what to do with a group once the project is finished. Sometimes people say 'oh yes, jolly good group, we'll find something else for them to do which will be a challenge.' But that usually doesn't work. You mustn't make projects just to employ people. You've got to disperse them around the projects which are now becoming the latest thing. They'll have to re-educate themselves. But you must move them from one challenging job to another and not just keep them together if they happen to be a good group... people liked to re-educate themselves." (Lawson, during our telephone conversation of 13-01-2005)

Although Dr. Lawson liked the process of re-education and finding new projects, he said it could be very challenging at times. He explained (during our first interview at his residence, 15-January-2004) that when a project came to an end he had to think of a new avenue to explore and, "if you haven't got an idea, then you can get a bit depressed." I responded to this remark saying: "But then if you <u>have</u> lots of ideas, and you like working

[141] Dr. Lawson, during our interview at his residence,15-January-2004.

[142] Sciama received his doctorate from the University of Cambridge in 1953 with Paul Dirac as supervisor. He himself supervised some 70 PhD students. As Ellis points out this included luminaries such as "Stephen Hawking, Brandon Carter (formulator of the Anthropic Principle in cosmology), Sir Martin Rees, Philip Candelas, John Barrow and David Deutsch (originator of quantum computing)." (Ellis, 2000, p.722)

independently, I suppose then it can be an advantage." Dr. Lawson replied, somewhat modestly: "Yes. Yes, well I had some ideas, I'm not sure that I had all that many. A lot of my ideas were in showing how things wouldn't work as they were being claimed, especially with new things." As mentioned in 7.2.4 Dr. Lawson's renowned abilities to critically evaluate new proposals may have stemmed from the 'affective transformation' he experienced in his 20s. Dr. Lawson's working environment in later years, where he was afforded the freedom to pursue his own research interests was an important factor in providing him with a broad view of physics and engineering. In fact, I would argue that this enabled him to notice analogies between several fields in physics and engineering and to synthesise and unify what was, at the time, a fragmented research area. This hypothesis is pursued in 7.2.8.

7.2.8 New views lead to illuminating analogues which continue during a varied career:

Many scientists have achieved new views through taking indirect routes. For example, Larry Holmes tells us that the 19th century physiologist,

> "Claude Bernard likened himself to a runner who chose not to follow the beaten path: 'Everyone follows his own path. Some have been trained for a long time and proceed by following the track that had been marked out. I myself have reached the scientific arena by indirect ways and have been freed from rules by running forth cross-country, which others perhaps would not have dared to do. But I believe that in physiology that has not been bad, because it has led me to new views'." (Holmes, 2004, p. xvii)

Case studies from the history of science underscore the creative value of making advances by noticing connections between different paths of enquiry. As mentioned in section 1.0 the historian and psychologist of science Howard Gruber refers to this as a 'network of enterprise.' (Gruber, 1980). This process of transferring concepts from one area to another involves a form of analogical reasoning. In the following comments, Gooding gives examples from the history of science, highlighting the differing levels of abstraction at which this process of transferring concepts can occur:

> "This can be achieved in several ways at different levels of abstraction. The most concrete and intuitive would be 'direct' recognition of a similarity at the perceptual level, such as Robert Young's recognition of similarities between the behaviour of water waves and ray-diagrams of optical inference (Miller, 1996). This would also rely on a fast cognitive processing that is closely coupled to evolved neural structures. At a more abstract level are similarities whose significance derives from being features generated by structural or process models in different domains. Examples are

> Faraday's recognition of the potential significance of relationships between the behaviour of electrical filaments (fig 9.14A), electrostatic lines (Fig 9.11E and 9.13) and magnetic lines (Fig 9.11C and 9.14). At a still higher lever of abstraction is his recognition of the significance of changes in the appearance of high frequency processes (e.g. acoustical patterns) with changes such as frequency and the density of the ambient medium (e.g. pitch of the sound made by the electric brush). Here...the ability to see the significance of similarities that are perceived 'directly' depends on deliberative kinds of reasoning with and about visual models of inferred or hidden processes. Communicating the meaning of these representations involves both deliberation and negotiation about them." (Gooding, 2005, p.210)

Dr. Lawson agreed that pursuing many paths of enquiry over a varied career was a key factor in his success as a scientist. He quipped: "I used to say that I was a 'jack of all trades and master of one'."[143] As he put it, "I've been a wanderer."[144] Interestingly, on the issue of getting mental pictures of the physical processes of his research, he said that being a wanderer was advantageous:

> "I realise more as I get older, that the mental pictures depend very much on your past experience, and what you know about already. And part of my advantage, is having been wandering around a lot from one thing to another over the years, I've collected a fairly broad sort of view point on things." (ibid.) [145]

(In section 7.3, I address the influence of visual memory on creativity and innovation.) Although Dr. Lawson agreed that the sources of much of his scientific inspiration (i.e. the material he synthesised and drew analogies from) came from a wide variety of branches of physics, he (characteristically) qualified this by saying: "within a limited range - there were some branches of physics that I knew nothing about..." [146] On joining Harwell after the war, Dr. Lawson encountered nuclear and quantum physics and, "immediately noticed striking parallels between wave mechanics and microwave radiation." He added: "Unconventional connections in the form of illuminating analogues came to mind and these continued at intervals during a varied career." [147] (These are discussed in more detail in the next chapter). Thagard (2005, p.165) notes that:

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[143] Dr. Lawson, during our telephone interview of 22-March-2004.

[144] Dr. Lawson, during, our first interview at his residence, 15-January-2004

[145] Of course one could argue that collecting a broad viewpoint on things can sometimes create confusion rather than lucidity. As mentioned in chapter 3, Richard Feynman alluded to this issue when he said: "I have a terrible confusion between the symbols I use to describe the objects and the objects themselves. I cannot really make a picture that is even nearly like true waves [...] When I talk about the electromagnetic field in space, I see some kind of superposition of all the diagrams which I've ever seen drawn about them." (Feynman, 1964. Quoted in Gooding, 1992, p.144)

[146] Dr. Lawson, during our telephone conversation of 22-03-2004

[147] Dr. Lawson, in his March 2003 letter to me.

> "Many successful scientists do not restrict their reading to the particular areas of research on which they are currently focused, but instead read widely, including work outside their field. This enables them to grasp analogies between current problems they face and established ones that may suggest new solutions. (Dunbar 2001; Holyoak & Thagard, 1995). Visual representations may facilitate analogical and other kinds of inference (Giere, 1999; Nersessian, 1992). Working on multiple projects with multiple methods may make possible new approaches to those projects."

Thus, I would argue that exploring five sub-fields of physics enabled Dr. Lawson to notice striking analogies between systems he encountered in different contexts. It may of course have been his ability to notice analogies that led him to pursue numerous lines of investigation in numerous fields. Whatever the direction of influence, this wider field of view, coupled with his excellent skills at analogical reasoning led to him making interesting connections - - identifying similarities between these diverse fields - - synthesising ideas and thereby providing his colleagues with a more unified view of the field. His use of analogies to bridge sub-disciplinary boundaries is discussed in chapter 8.

7.3 The Influence of Visual Memory on Creativity & Innovation

Oppenheimer (1956, p.130) has remarked that:

> "Whether or not we talk of discovery or of invention, analogy's inevitable in human thought, because we come to new things in science with what equipment we have, which is how we have learned to think, and above all how we have learned to think about the relatedness of things. We cannot, coming into something new, deal with it except on the basis of the familiar and the old-fashioned."

There are many instances from the history of science that underscore Oppenheimer's remarks. For example, Gorman (2005) has shown how Alexander Graham Bell's telephone was based "on the visual and kinaesthetic analogy to the human ear that was unique to his experience and expertise (Gorman, 1997)." (Gorman, 2005, p.293). In discussing the mechanical representations used by Faraday in his invention of the first electromagnetic motor, Gooding tells us that:

> "These mechanical representations can be retained in memory; moreover, they are so well understood that their use will be consistent and the implications of their properties for other components of a device can readily be worked out." (Gooding, 1990b, quoted in Gorman, 1998, p.25)

Dr. Lawson's visual memory seems to have played an important part in his work. He had many visual and analogical resources at his disposal and employed them successfully to acquire and promote insight. As mentioned in 7.2.8, Dr. Lawson explained that the wandering nature of his career path has been instrumental in equipping him with these resources. A scientist's residual memories can be particularly influential in the early stages of their research. To use an analogy, one could compare it to a hysteresis effect in physics, where a physical system has a strong *history* dependence. Eugene Ferguson tells us that in the field of engineering:

> "When designers are thinking out their preliminary designs, their visual memories are particularly influential. Mark Clark has found significant visual similarities between components of the docking mechanism of spacecraft and the landing gear of airplanes. The designers of the docking mechanisms had been recruited from the pool of aircraft designers who had a great deal of experience with landing gear. The similarities, often subtle, became evident to Clark only as he became familiar with both airplane landing gear and docking mechanisms." (Ferguson, 1992, p. 15 & 16)

I quoted Ferguson in follow-up exchanges with some of my questionnaire respondents. **Phys_200**, a retired engineer with experience in the construction industry, replied saying:

> "Your space docking quote is nothing more than I/one would or should expect. One builds on one's experience to solve the next problem. So 'landing gear' experience is the most recent knowledge base and so is the first stop for 'off the shelf' knowledge when looking for solutions for solving the next problem." (Phys_200b)

Drawing on decades of personal experience in the fields of physics and engineering he added:

> "I spent my whole working life cross-fertilising ideas across from one experience base/industry/project to another, or from one colleague to another. There is very little that is new in this world, just new ways of adapting known information (knowledge) across boundaries to solving the next problem that may or may not be in the same application domain. Many people however are so compartmentalised that that cannot think out of the box. It is then the job of others to gather this knowledge base and use it/disseminate it more widely and so build on to solve the next problem...." (Phys_200b)

Dr. Lawson is one such out-of-the-box thinker who, to paraphrase **Phys_200,** gathers a broad knowledge base and then uses it and disseminates it more widely, building on it to solve the next problem.

7.4 Dr. Lawson: The Synthesiser & Translator

Nersessian's cognitive-historical studies of the work of J.C. Maxwell show him to be a synthesiser of extraordinary prowess. According to Nersessian:

> "Maxwell derived the field equations through a constructive modelling processes that involved synthesizing multiple constraints drawn from the physics of elastic fluids and of machine mechanisms, experimental data on electricity and magnetism, Faraday's hypotheses about the lines of force and his models, William Thompson's hypotheses of rotational motion of magnetism and his analogies, and mathematical equations." (Nersessian, 1995, p.212)

The cosmologist Dennis Sciama was also renowned for having "a strong flair for synthesis" [148] drawing on his "broad knowledge of physics to make fruitful connections among many topics in astronomy and astrophysics." [149] There is ample evidence from Dr. Lawson's scientific papers and book to support the proposition that **synthesis** is also a prominent feature of Dr. Lawson's mode of thought. (See tables 8.2a & 8.2b in section 8.4). When asked (during our telephone conversation of 22-March-2004*)* whether he would describe himself as "a synthesiser," he replied, "yes, I would say that." He is (and by his estimation, has always been [150]) skilled at making interesting connections between things, and synthesising these viewpoints into a more unified and coherent picture. In general, Dr. Lawson synthesised on a phenomenological level, with the aim of acquiring and or promoting physical or pictorial insight. For example, comparing ion beams to drifting gases or bags filled with water, in order to get a 'feel' for how particles behave. In this respect his modelling techniques were akin to those of Faraday. As Gooding (1990, p.23) tells us: "... Faraday needed to use images and words about images to overcome the ephemerality of his construals of new experience. His record and the instructions it contains become part of the world from which stable, communicable experience emerged." Being a synthesiser was to a certain extent dependent on Dr. Lawson's profession: His working environment (at the Rutherford Appleton Laboratory) consisted of physicists and engineers of differing backgrounds and research interests. An individual who could act as a synthesiser and unifier of concepts, jargon, notations, etc. was extremely valuable in such a working environment. (In section 8.3 I discuss his ability to act as a 'translator' of languages, ideas and notations between practitioners his field. I give examples from his

[148] Quoting CERN Courier.
Source: http://www.cerncourier.com/main/article/40/4/18/1 (Accessed 19-08-2005)
[149] Quoting Wikipedia Source: http://en.wikipedia.org/wiki/Dennis_William_Sciama (accessed 19-08-2005)
[150] "I'd always been able to do that [i.e. see connections between things]. I mean my very first paper which is a good example of analogy which is interesting. When I look at that paper I'm surprised how interesting that is." (Dr. Lawson, during our telephone interview of 13-01-2005)

scientific papers and book, highlighting his use of analogy and synthesis to provide these experts and intermediates with physical and pictorial insights). Announcing his election as a Fellow of the Royal Society, a Rutherford Appleton Laboratory bulletin said of Dr. Lawson:

> "Though making significant contributions in many specific areas of accelerator physics, perhaps his most notable achievements have resulted from his ability to survey, in both breadth and depth, the underlying theoretical principles of the science, identify where gaps appear in the theory, and to fill them." (Rutherford Appleton Laboratory, Bulletin number 5, 6-April- 1988)

It went on to say that Dr. Lawson's:

> "work on the use of lasers to accelerate particles was described as 'another example of the way in which he can enter a newly developing field of study and single-handedly bring order where none existed before'." (ibid)

This type of evidence is obviously biased, portraying Dr. Lawson in a positive light only. As Dr. Lawson himself quipped, "they always say nice things about you on such occasions." [151] However, like an obituary, it not only provides information on the characteristics of the individual in question, it also provides a snapshot of the period, indicating which personal characteristics were particularly valued at the time, e.g. the ability to unify a diverse field, bringing order where none existed before.[152] Such evidence, though biased, does help to paint a more vivid picture of the atmosphere in which Dr. Lawson worked. In fact, in response to questioning concerning his particular ability to act as a synthesiser, he played down his own abilities, re-directing attention to the atmosphere in which he worked, saying:

> "... a lot of this depends on the state that the subject is in, if it's ready for some degree of synthesis, because - - before the war, I mean there would have been different fields, particle beams which were separate - - and it was time, if you like, for them to come together a bit more. So if I hadn't done it, I suppose other people would have done. But I was particularly good at it. And I certainly had invitations to go here there and everywhere, which is why I did a lot of travelling." [153]

Dr. Lawson's synthetic tendencies are particularly evident in his book, *The Physics Of Charged Particle Beams* (1988, 2nd ed.), which provides an extensive overview of the physics of charged particle beams. Throughout this 446-page book, Dr. Lawson attempts "to bring together and compare all commonly used versions," of things. (Lawson, 1988, p.12).

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[151] Dr. Lawson during our telephone conversation of 13-01-2005
[152] Thanks to Dr. Chris Philippidis for his useful comments on this issue.
[153] Dr. Lawson, during our telephone conversation, 12:00-12:30, 22-March-2004

During our first interview, Dr. Lawson read aloud from the introduction of the book in order to emphasise the essence of his synthetic style of thinking. He read:

> " 'Charged particle beams are widely used in scientific, industrial and even domestic apparatus, i.e. the television. The physical properties of such beams have been studied by workers in many different fields, often at different times, in rather different contexts... Nevertheless, despite differences in function and superficial appearance, beams used in a wide variety of applications will be shown to have to have many features in common. This is sometimes obscured by differences of approach or notation. In this monograph, the unity of things encountered in different contexts is emphasised and classification is in terms of physical features rather than application... The approach is synthetic, simple examples are considered first, and the complications introduced gradually... Nevertheless, it presents a more vivid way of the essential physical ideas, which form a set of conceptual building blocks that are useful when trying to think about new situations, and to understand their inherent limitations'."

He elaborated on the quotation from his book, adding:

> "So I'm saying there, that there are examples of people doing quite similar things in different contexts, and in some - - one or two papers for instance - - it shows that the essential result in one is either identical with or closely related to a well-known result in another field. So, if you understand both those general results, then you've got a wider view, and you can go out from that. And it's especially in the time that new ideas are being tossed around that you want to be able to do this. But you've also got to be able to be critical and disregard things, and when you first see something, you've got to say 'ok, that's one thing, but what are the wider - - what other things'... " [154]

Thus, Dr. Lawson's book aims to highlight the deep connections between different physical ideas in the hope that these "conceptual building blocks" can be used as scaffolding when attempting to extend ones understanding in to a new area of interest. (See section 5.6 for questionnaire respondents' remarks on their use of analogy as scaffolding). Dr. Lawson's use of analogy as a 'bridging' device between practitioners in the fields of e.g. microwave tube, accelerator and plasma physics is discussed further in section 8.5. I discuss Dr. Lawson's role as a 'translator' between different 'languages of thought' among 'sub-cultures' of physicists and engineers in section 8.3, however, as it is a key characteristic of his thinking style, and our conversations about his role as a translator revealed other personality traits, I will briefly introduce in this chapter.

When I questioned Dr. Lawson on his ability to communicate science effectively, he told me: "I was known for my broad insights, often invited to give opening or summing up

[154] Dr. Lawson, during our first interview at his residence, 15-Jan-2004

talks at conferences," [155] The hope was that he may "spark off new approaches" [156] in the field. He was also often asked by journal editors to write introductory articles on emerging physics (e.g. Lawson, Dr., (1979), *Free Electron Lasers.* **Nature Vol. 277, p. 262**). He said he, "spent a lot of time" doing lectures at conferences and attending workshops, adding:

> "I was quite - - well, my style was, I think, quite popular, in that I was, you know, invited all over the place. I went to various European countries - Poland and Romania - Hungary, and I had a special invitation to Russia and to China ... and I spent some time in Japan. So these were all just because I seem to have got a reputation for putting things in a way that people liked -- it must have been I think." [157]

It is worth noting that the above excerpt contains considerable 'hedging'. [158] The linguist Greg Myers (1991) defines hedges as: "a wide range of features modifying the strength of an assertion or membership in a category with a modal, an advert or adjective, or a parenthetical comment." (Myers, 1991, p.44) Hedging is used in order to reposition oneself, to convey politeness, tentativeness, uncertainty, etc. in speech or writing. Dr. Lawson's use of qualifying words such as: "quite", "well", "I think", "you know", "just", "seem" etc. in this excerpt, reflect what he later termed his, "strange mixture of modesty and the opposite." [159] Thus, Dr. Lawson exhibits the characteristics of a synthesiser and translator.

7.5 Dr. Lawson: The Innovator?

In section 5.4 I showed that questionnaire respondents who were enthusiasts for using analogy in their research also tended to generate original analogies to a greater extent. Thus, in the case-study, I was interested to explore whether or not enthusiasts for analogy tended to be particularly innovative: In the sense of linking apparently unrelated things, synthesising ideas and creatively reformulating them, presenting new dimensions to the viewer. This hypothesis presupposes a distinction between our ordinary, everyday use of analogy and particularly creative ones. The similarities should extend beyond surface similarity to deeper, mathematical similarities. In our first interview (13-01-2004) Dr. Lawson showed signs of being innovative, saying that: "as a boy, I was always making things... usually I had no resources because we weren't very well off, and it was a question

[155] Dr. Lawson, in reply to my questionnaire of 04-10-2004

[156] Dr. Lawson, in the conclusion of his **"Diversity and unity in sources and beams"** paper, delivered at Brookhaven in 1971

[157] Dr. Lawson, during our first interview at his residence on15-January-2004

[158] Lakoff (1972) first introduced the term 'hedges' in his article, *"Hedges: A Study in Meaning Criteria and the Logic of Fuzzy Concepts."*

[159] "Well I'm a strange mixture of modesty and the opposite, or so my wife thinks anyway." (Dr. Lawson during our telephone conversation of 13-01-2005)

of using bits and pieces of anything else, and scrounging... which was very good for me really... " But later in the same interview, while acknowledging that he had "some ideas" during his career, he added (perhaps modestly): "I'm not sure that I had all that many. A lot of my ideas were in showing how things wouldn't work as they were being claimed, especially with new things." (ibid.). Again, in a telephone conversation of 22-03-2004 he showed innovative tendencies. Firstly, when discussing the tools, techniques and problem solving techniques he used in his work, he said: "Often if there's a complicated problem that you don't quite know how to tackle, the thing is to **invent** a simpler problem of the same class, which you think you can tackle." (ibid). This fits into Kuhn's (1962) theoretical framework regarding the use of 'exemplars' as puzzle-solving devices in science. It also reminds of us the joke about assuming one is dealing with a spherical horse travelling through in a vacuum (cf. section 8.4). Secondly, when discussing physical insight, Dr. Lawson explained that, due to his preference for pictorial rather than mathematical thinking: "I have to **invent** my own way of thinking about particular problems. Just seeing how certain problems seem to be related in one way or another." (ibid.) Yet when asked if he would describe himself as **innovative** he responded: "Not particularly. I don't think I've invented any new thing, but I'm a good critic really." (ibid.) Dr. Lawson appears to be follow the conventional view, outlined by Mehus, that:

> "...a person who merely solves well-defined problems is not considered as creative, even not if one of these problem solutions turns out to be highly innovative. Also, if a problem solver arrives at the solution of an ill-defined problem in a non-rational way (for instance, by modifying well-founded constraints in an unjustified way), he or she is not viewed as creative." (Mehus, 1999, pp.200-201)

According to Gruber,

> "[A creative scientist] has a point of view that is different from others, and it is this point of view that permits him to see things in a new way, to see new questions, new opportunities, new directions to go in. He is not really a better problem solver than his similarly gifted contemporaries, or many of the other experts around him." (Gruber, 1985, p.178)

I share Gorman's view that: "Taken together, heuristics, mental models and mechanical representations allow us to study and compare the cognitive styles of inventors and discovers, by which I mean the manner in which each individual practitioner finds, transforms and solves problems." (Gorman, 1998, p. 125). My methodological and theoretical framework was influenced by Gorman's (1998) five generalisations concerning cognition, invention and discovery. That:

1. Invention depends on establishing that a problem is significant enough to be labelled an important achievement.
2. Invention depends on transforming that problem into a form that suggests a promising path to solution which includes locating and transforming the necessary mechanical representations.
3. Invention depends on a combination of flexibility and stubbornness, depending on the cognitive styles and the career trajectories of the inventors involved and on how they represent the problem.
4. The act of writing is part of the invention process.
5. Successful inventors often pursue a network of enterprises.

Upon further reflection, it may have been better to use the term **"creative"** as well as the term **"innovative"** when exploring this issue with Dr. Lawson. The term **"innovative"** may have suggested something **tangible,** i.e. something that impacts on one's surroundings, as opposed to a **private mental construct,** used as a problem solving strategy in one's work. As I noted in section 1.5, there are different types of creativity: big-C creativity and little-c creativity, personal and socio-cultural. According to an infamous marketing slogan: *"Creativity is thinking up new things. Innovation is doing new things."* [160] If this view were to be transferred to Dr. Lawson's domain, designing, building and introducing a new piece of equipment to one's 'culture', or developing and disseminating a new experimental methodology amongst one's peers, would be regarded as 'innovative', but creating or inventing alternative ways of reasoning, (e.g. through drawing analogies), would not. In my view, however, the slogan cannot be transferred to the domain of physics. There is no dichotomy between doing and thinking for physicists and engineers: thinking & doing interact e.g. in solving equations, computer modelling, designing or modifying equipment, designing or modifying experiments, model building, etc. Of course, the degree of inventiveness will vary. For example with respect to analogy, it may depend on whether one is drawing from a stockpile of tried and tested analogies, or generating original analogies. As discussed in chapter 6, generating original analogies is almost certainly more common when one is **'playing'** with ideas: when one is figuring things out for oneself (in the early stages of conceptualisation) and also when one is communicating ideas in a playful, relaxed setting. When publishing research in a peer reviewed journal, one may err on the side of caution, either reverting to well established analogues, (e.g. simple harmonic oscillator), or simply omitting the analogues which were used as scaffolding in the early stages of conceptualisation.

[160] Attributed to the marketing specialist, Theodore Levitt, author of numerous books on imagination and innovation in marketing.

7.6 When the act of arranging information becomes an act of insight

Dr. Lawson frequently uses a structured, symmetrical form of graphical display in his book on the physics of charged particle beams and his published and unpublished papers. Many engineering textbooks employ a similar technique to make material accessible by facilitating cross comparison. However, Dr. Lawson's use of tables seems to go beyond the customary textbook use. It may play a key role in his ability to acquire insight and may be linked to his ability to reason analogically. As discussed in chapter 1, a large body of research suggests that reasoning by analogy involves a type of *structure alignment* or *structure-mapping* between domains (e.g. Gick and Holyoak 1980; Gentner, 1982, 1983; Gentner and Gentner 1983; Gentner and Clement 1988; Holyoak and Thagard 1989; Ross 1989; Markman and Gentner 1993; Halford 1992;) As Gentner & Gentner explain: "[A] structure-mapping analogy asserts that identical operations and relationships hold among non-identical things. The relational structure is preserved, but not the objects." (1983, p.102). Also, there is reason to believe that one's interpretation and representation of problems affects one's solution strategy. (cf. Kintsch & Greeno, 1985). The observed differences in problem solving strategies between experts and novices may result from experts possessing superior representations of problems: experts often use higher-order categorizations, e.g. conservation laws (cf. Chi, Feltovich and Glaser, 1981). Playing with and rearranging data often allows new features to emerge. Michael Faraday, for example, used physical models and apparatus to play with possibilities and used matrices to do systematic structure or feature mapping. (Gooding, 2005, p199). By rearranging and systematically representing data of two systems (A and B) having similar features, additional similarities between A and B may emerge through analogical reasoning (e.g. extrapolations involving higher order categorizations). According to Edward Tufte (statistician, graphic designer and founder of *Graphics Press*):

> "[C]larity and excellence in thinking is very much like clarity and excellence in the display of data. When principles of design replicate principles of thoughts, the act of arranging information becomes an act of insight." (Tufte, 1997, p.9)

I will now present an example from Dr. Lawson's scientific papers which shows that form, pattern and structure when displaying data appear to be key features of his style of thinking. (Three more examples are provided in appendix 7, sections A7.3-A7.5). In chapter 8 I will elaborate on Dr. Lawson's use of analogy and synthesis to provide insights when conceptualising and communicating physics to experts and intermediates in sub-fields related to accelerator design.

7.6.1 Waveguides & Wave Mechanics Some Similarities & Differences (Eg1)

The following extract is from an unpublished paper, based on a lecture given on 15th December 1950, when Dr. Lawson was 27 years old. In this paper, Dr. Lawson highlighted the strengths and weaknesses of drawing "analogies between the fields in a waveguide and Schrödinger's equation in one dimension". This paper provides a striking example of Dr. Lawson's preference for form, structure and symmetry in the presentation of his material. Dr. Lawson constructs a table composed of 15 sketches (see fig.7.3 overleaf).

- row 1 shows a physical representation of the waveguides, i.e. material media that confine and guide a propagating electromagnetic wave, something which Dr. Lawson may have made by hand;
- row 2 shows a quantum mechanical viewpoint of different particles trapped in a potential-wells;
- row 3 shows a graphical sketch of the wavefunctions;
- row 4 indicates whether or not they are bound states.

As Dr. Lawson explains in his paper on Waveguides and Wave Mechanics:

> "The first two diagrams show a finite number of resonant frequencies (bound levels) and a continuum of propagated frequencies (free levels) of higher frequency (energy). The third diagram shows an unquantised system, which is capable of having any values of n, (W). The point where the waveguide decreases below the cut off size (classical distance of closest approach) moves nearer to the origin as the frequency (energy) increases. The fourth diagram shows two coupled systems. If there is a length of cut off waveguide (potential barrier) between the two systems, this results in a splitting of the resonant frequencies (energy levels) of the system, considered independently. If the connecting waveguide is narrow (potential barrier is large) the splitting is slight, and the electromagnetic energy (particle) flows slowly from one system to the other and back. At frequencies so high that the connecting waveguide no longer cuts off (energies higher than the potential of the barrier between the system) the system again behaves as a single resonator (oscillator)... In considering the fifth diagram in the figure, we shall see where the analogy ends..."

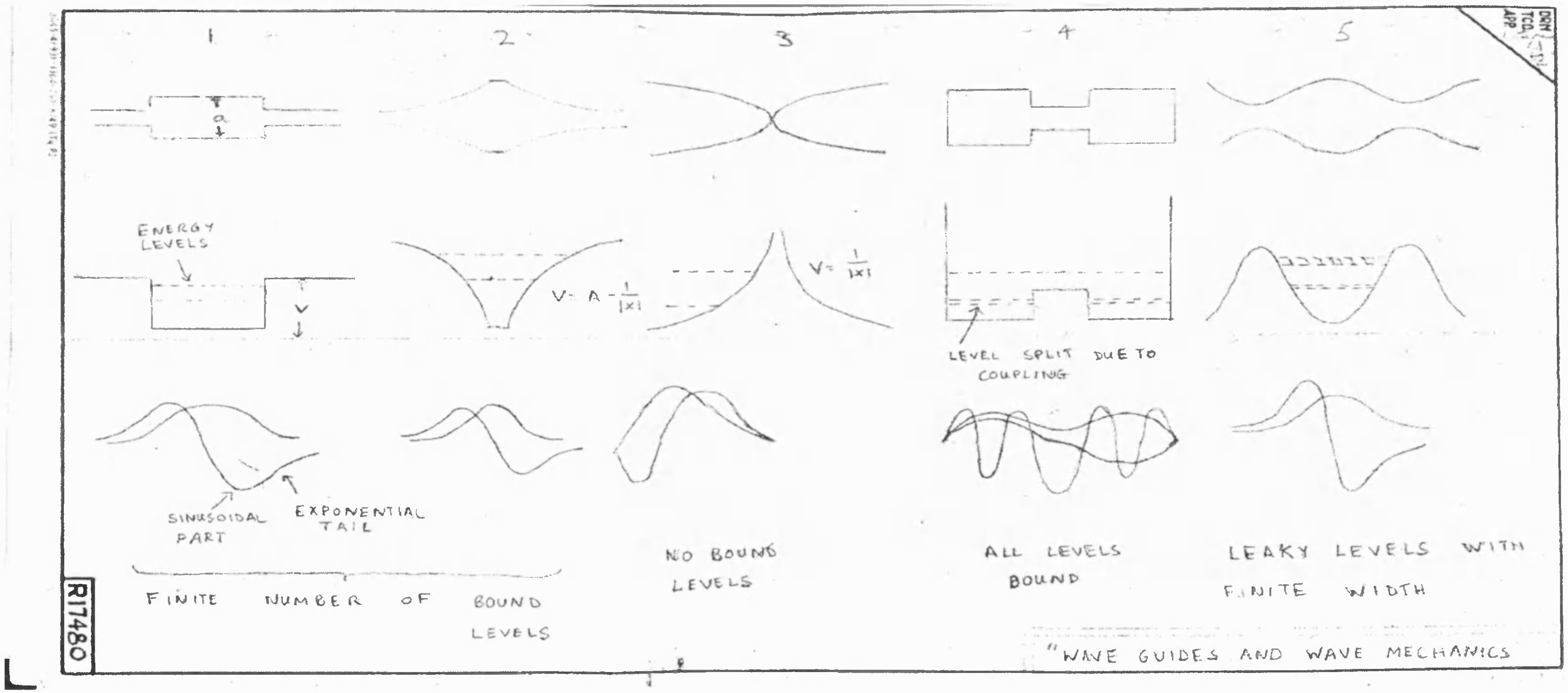


Figure 7.3 – Matrix of sketches from Dr. Lawson's paper on *"Wave Guides and Wave Mechanics: Some Similarities and Differences"*. These are the figures to which Dr. Lawson is referring in his annotation, when he says, "To me the figures say everything."

Dr. Lawson employs this method to highlight the analogy between the fields in a waveguide and Schrödinger's equation in one dimension. He seems to be guided by pictorial heuristics and diagrammatic reasoning, much more than by formal mathematical analogues. It should be noted that the mathematics for both systems has the same underlying structure. A theoretical physicist, who does not share Dr. Lawson's practically orientated education, may not regard this as an analogy, merely different instances of the same thing. Thus, this is a telling example of the way in which Dr. Lawson's educational and professional background may have informed his viewpoint.

The table of sketches has a progressive aspect to it, with each column illustrating the different outcomes for waveguides of various shapes and forms. The viewer is led step-by-step from a simple case to a more complicated case; one might even be left imagining what column 6 might look like. In a post-it note annotation to this paper, Dr. Lawson remarked that to him, "the figures [i.e. sketches] say everything." When I pursued this during a follow-up conversation he told me he does not make a conscious effort to present material in this structured manner. As he put it, "it's just the way I think." When I asked him if the arrangement of information was a means of acquiring or promoting insight, Dr. Lawson responded: "Promoting – I chose what seemed to be the simplest and most elegant layout." [161] When asked how theory informed his choice and arrangement of diagrams, he responded: "I didn't consider 'theory' especially – just general clarity." (ibid.) In response to the question of who his imagined audience were, Dr. Lawson said:

> "During the war I worked on microwaves, afterwards I moved to a field involving some nuclear physics. The points of similarity immediately struck me and gave rise to this informal lecture to immediate colleagues. This simple comparison is original, and is developed in later papers." (ibid.)

To show "where the analogy ends" in his paper on waveguides and wave mechanics, Dr. Lawson uses some mathematical manipulation, (which should be familiar to anyone who has studied physics or mathematics at degree level). On page 3 he shows the relation between the 'complex' energy and the wavefunction, and graphically parallels the frequency spread with the energy spread about the mean. The visual presentation of the equations is noteworthy. Dr. Lawson presents them in parallel, with an axis of symmetry down the centre (see figures 7.4 and 7.5 on the next page). This is similar to his presentation of figures 1 to 5 shown as figure 7.3 above. Bear in mind that this paper was type-written in 1950, before word processors made it easy to present data in a symmetrical arrangement. The manner in which Dr. Lawson arranges the mathematical equations

[161] Dr. Lawson, 04-10-2004, in response to my questionnaire of 15-Aug-2004.

(presented in parallel, with an axis of symmetry) and the graphical figures (presented in parallel, in an ordered table) facilitates cross comparison. It is a technique in widespread use in physics textbooks[162] although, to the best of my knowledge, few empirical studies have been conducted to test the effectiveness of this technique as a means of making material accessible to the reader. [163] See appendix 7 for a table outlining some commonly used "Interdisciplinary Electrical Analogies." One could argue that he would not have organised his data (equations, graphical figures, visual matrices, etc.) in a structured manner if he did not foresee the paper being read by others, i.e. if he did not have an 'addressee' in mind. (see e.g. Dixon, Deets, & Bangert, 2001, p. 462). Or as the linguist Bakhtin would say, Dr. Lawson's paper was: "addressed to a particular group of readers with a particular apperceptive background of responsive understanding." (Bakhtin, 1986, p.96). Having viewed many of Dr. Lawson's unpublished notes, and spoken to him at some length on the topic, I have concluded that he does tend to organise data in this highly structured manner, regardless of whether or not it is intended for subsequent publication.

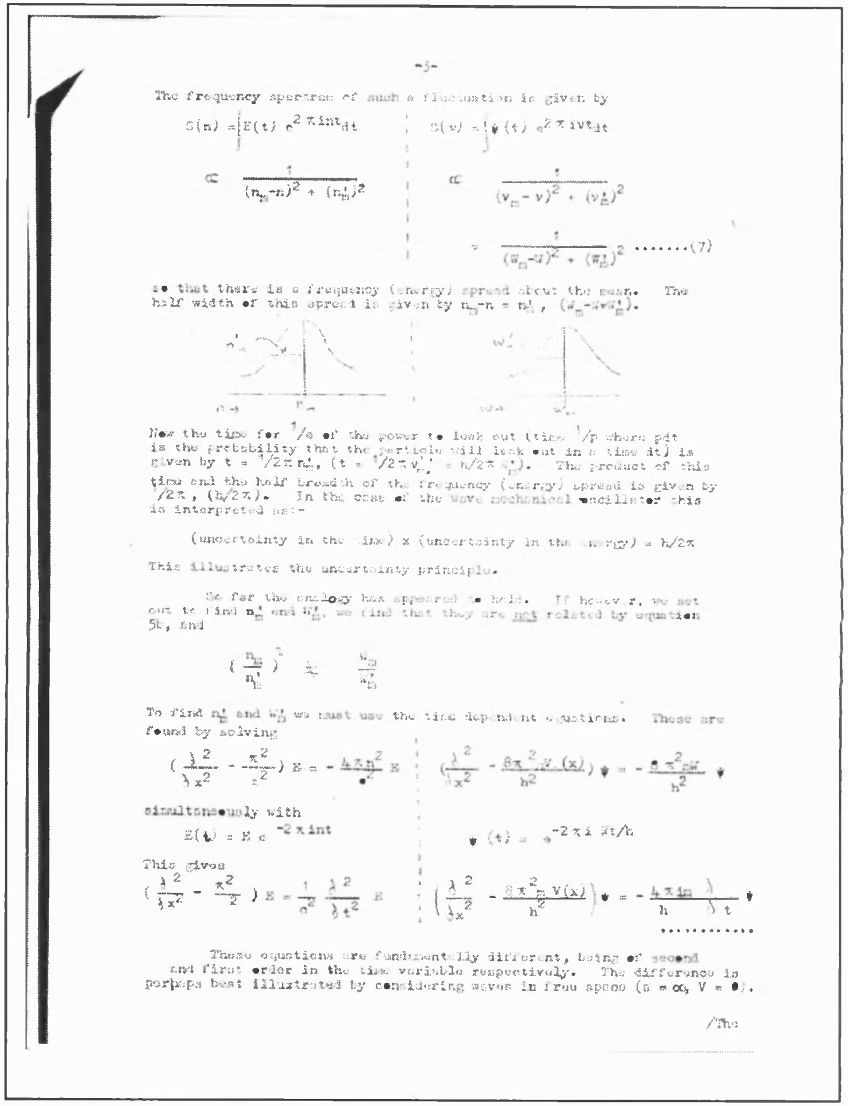
In fact, as Dr. Lawson's preference for form and structure extends beyond physics into the realms of music, art and poetry, suggesting that it may be a key facet of his cognitive style. This fact arose in our first interview, when I questioned Dr. Lawson on whether he had poetic tendencies. Dr. Lawson said that he particularly enjoyed the sonnets of Keats and Wordsworth that had "form and structure" where "you have to express your ideas within a formal framework and that's a sort of challenge." When asked if he himself wrote any poetry, Dr. Lawson replied (perhaps somewhat bashfully): "Ahm, no I don't. I write doggerel verses on occasions, you know, peoples' retirement or something of that sort. But it's just doggerel, you know, rhyming couplets. {gentle laugh}." (ibid.) [164] Dr. Lawson went on to say that also within the visual arts and in music, "I enjoy things that are <u>structured.</u>" [165] Thus Dr. Lawson has a preference for form and structure that is both **visual** and **aural** (through rhyme and metre in poetry, and his appreciation for Bach's music in particular). The fact that this preference for structure extends beyond physics strongly suggests that it is a prominent feature of his cognitive style and may be influential in his analogical reasoning abilities.

[162] From Mott & Sneddon's (1948) *Wave Mechanics and it Applications* to Serway & Beichner's (2000, 5th Edition), *Physics: For Scientists and Engineers.*

[163] Paul Hewitt's series of textbooks and interactive learning tools stemming from **Conceptual Physics** work goes some way however. Can be found at URL: http://www.conceptual physics.com/index.shtml (accessed on 25-07-2005)

[164] Of course the ability to write beautiful and/or satirical verse, which has form and structure, is regarded by some as the sign of a 'true' poet. As the formalist poet Robert Frost is reputed to have said, "Writing free verse is like playing tennis with the net down."

[165] Dr. Lawson, during our telephone conversation, 12:00-12:30, 22-March-2004



-3-

The frequency spectrum of such a fluctuation is given by

$$S(n) = \int E(t)\, e^{2\pi i n t}\, dt \qquad ; \qquad S(\nu) = \int \psi(t)\, e^{2\pi i \nu t}\, dt$$

$$\propto \frac{1}{(n_m - n)^2 + (n_m')^2} \qquad ; \qquad \propto \frac{1}{(\nu_m - \nu)^2 + (\nu_m')^2}$$

$$= \frac{1}{(W_m - W)^2 + (W_m')^2}\ \text{.......(7)}$$

so that there is a frequency (energy) spread about the mean. The half width of this spread is given by $n_m - n = n_m'$, $(W_m - W = W_m')$.

Now the time for $^1/e$ of the power to leak out (time $^1/p$ where pdt is the probability that the particle will leak out in a time dt) is given by $t = {}^1/2\pi n_m'$, $(t = {}^1/2\pi \nu_m' = h/2\pi W_m')$. The product of this time and the half breadth of the frequency (energy) spread is given by $^1/2\pi$, $(h/2\pi)$. In the case of the wave mechanical oscillator this is interpreted as:-

(uncertainty in the time) x (uncertainty in the energy) = $h/2\pi$

This illustrates the uncertainty principle.

So far the analogy has appeared to hold. If however, we set out to find n_m' and W_m', we find that they are not related by equation 5b, and

$$\left(\frac{n_m}{n_m'}\right)^2 \neq \frac{W_m}{W_m'}$$

To find n_m' and W_m' we must use the time dependent equations. These are found by solving

$$\left(\frac{\partial^2}{\partial x^2} - \frac{\pi^2}{a^2}\right) E = -\frac{4\pi n^2}{c^2} E \qquad ; \qquad \left(\frac{\partial^2}{\partial x^2} - \frac{8\pi^2 m V(x)}{h^2}\right)\psi = -\frac{8\pi^2 m W}{h^2}\psi$$

simultaneously with

$$E(t) = E\, e^{-2\pi i n t} \qquad ; \qquad \psi(t) = e^{-2\pi i W t/h}$$

This gives

$$\left(\frac{\partial^2}{\partial x^2} - \frac{\pi^2}{a^2}\right) E = \frac{1}{c^2}\frac{\partial^2}{\partial t^2} E \qquad ; \qquad \left(\frac{\partial^2}{\partial x^2} - \frac{8\pi^2 m V(x)}{h^2}\right)\psi = -\frac{4\pi i m}{h}\frac{\partial}{\partial t}\psi$$

....

These equations are fundamentally different, being of second and first order in the time variable respectively. The difference is perhaps best illustrated by considering waves in free space ($a = \infty$, $V = 0$).

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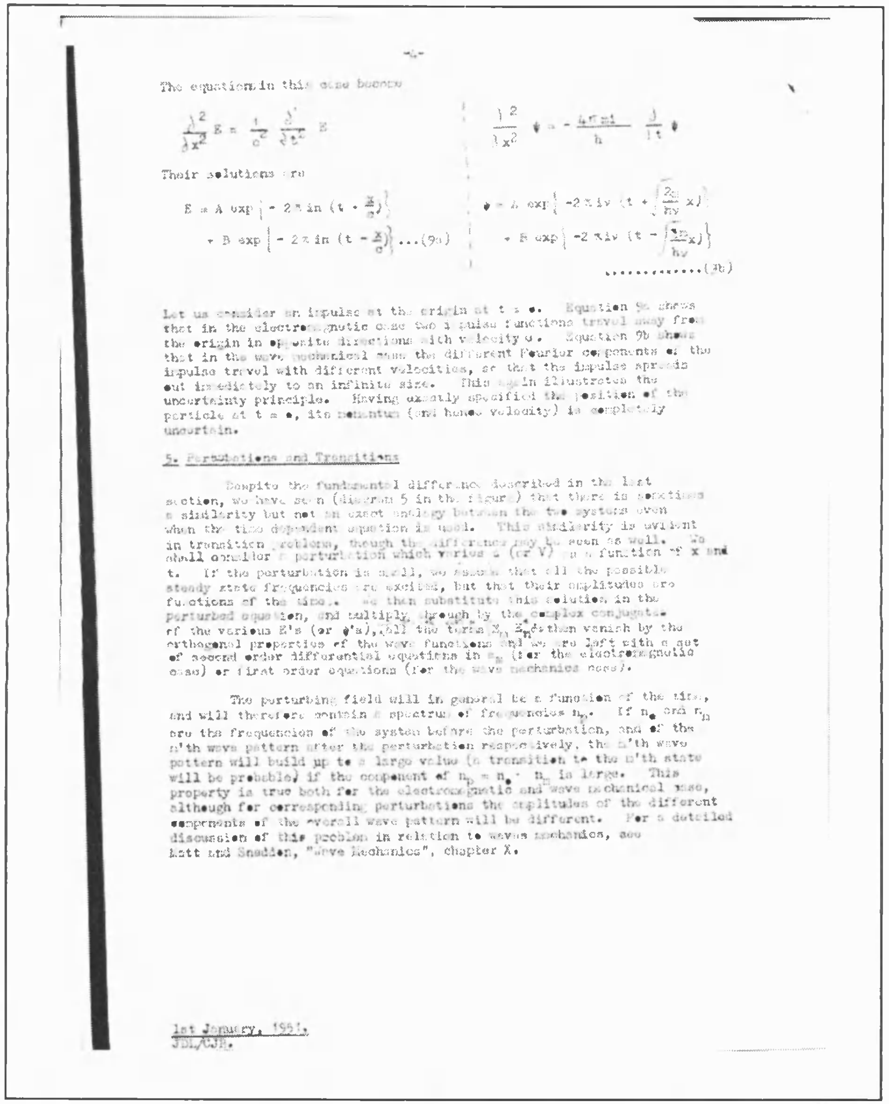

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The equations in this case become

$$\frac{\partial^2}{\partial x^2} E = \frac{1}{c^2}\frac{\partial^2}{\partial t^2} E \qquad ; \qquad \frac{\partial^2}{\partial x^2}\psi = -\frac{4\pi m i}{h}\frac{\partial}{\partial t}\psi$$

Their solutions are

$$E = A \exp\left\{-2\pi i n\left(t + \frac{x}{c}\right)\right\} + B \exp\left\{-2\pi i n\left(t - \frac{x}{c}\right)\right\} \text{...(9a)}$$

$$\psi = A \exp\left\{-2\pi i\nu\left(t + \sqrt{\frac{2m}{h\nu}}\,x\right)\right\} + B \exp\left\{-2\pi i\nu\left(t - \sqrt{\frac{2m}{h\nu}}\,x\right)\right\} \text{..............(9b)}$$

Let us consider an impulse at the origin at t = 0. Equation 9a shows that in the electromagnetic case two impulse functions travel away from the origin in opposite directions with velocity c. Equation 9b shows that in the wave mechanical case the different Fourier components of the impulse travel with different velocities, so that the impulse spreads out immediately to an infinite size. This again illustrates the uncertainty principle. Having exactly specified the position of the particle at t = 0, its momentum (and hence velocity) is completely uncertain.

5. Perturbations and Transitions

Despite the fundamental difference described in the last section, we have seen (diagram 5 in the figure) that there is sometimes a similarity but not an exact analogy between the two systems even when the time dependent equation is used. This similarity is evident in transition problems, though the difference may be seen as well. We shall consider a perturbation which varies a (or V) as a function of x and t. If the perturbation is small, we assume that all the possible steady state frequencies are excited, but that their amplitudes are functions of the time. We then substitute this solution in the perturbed equation, and multiply through by the complex conjugates of the various E's (or ψ's), all the terms $E_n E_m^*$ then vanish by the orthogonal properties of the wave functions and we are left with a set of second order differential equations in a_m (for the electromagnetic case) or first order equations (for the wave mechanics case).

The perturbing field will in general be a function of the time, and will therefore contain a spectrum of frequencies n_p. If n_o and n_m are the frequencies of the system before the perturbation, and of the m'th wave pattern after the perturbation respectively, the m'th wave pattern will build up to a large value (a transition to the m'th state will be probable) if the component of $n_p = n_o - n_m$ is large. This property is true both for the electromagnetic and wave mechanical case, although for corresponding perturbations the amplitudes of the different components of the overall wave pattern will be different. For a detailed discussion of this problem in relation to waves mechanics, see Mott and Sneddon, "Wave Mechanics", chapter X.

1st January, 1951.
JDL/CJR.

Figures 7.4 & 7.5: Extracts from Dr. Lawson's paper on "Wave Guides and Wave Mechanics: Some Similarities and Differences"

7.7 Conclusions:

In this chapter, I have provided an outline of Dr. Lawson's research background in order to show that several factors must be taken into account when considering the conceptualisation and communication techniques he found useful in his work. These are:

(i) His early childhood experiences;
(ii) His formal education;
(iii) His working environment during his formative years;
(iv) A "slightly traumatic" event which occurred during his first project;
(v) His Personality;
(vi) Luck;
(vii) His working environment in later years - the freedom to pursue his own research interests;
(viii) How new views led to illuminating analogues which continued during a varied career.

Table 7.1 summarises several characteristics which Dr. Lawson exhibits which are relevant to the conceptualisation and communication tools he uses in his work. The background information discussed in this chapter provides us with a better understanding of two key characteristics displayed by Dr. Lawson: that of a **synthesiser** and of a **translator**. His training, research background and working environment all contributed to the fact that he synthesised ideas from a variety of sub-fields (e.g. applied optics, plasma physics, high-energy and particle physics, and astrophysics) and acted as a translator bridging conceptual divides between sub-cultures of physicists and engineers. Dr. Lawson often employed mathematical, physical and pictorial analogies to do this. This will be discussed further in chapter 8.

Discussed in section	Characteristic	Example from analysis of 30 of his scientific papers, his book and personal correspondence we carried out.
7.2.2	Physicist-Engineer with degree in mechanical sciences	"I think pictorially and **not** mathematically." [166] "I had a Faraday-type approach where most of my colleagues were Maxwell like." [167] In his experience, engineers tend to have their "feet on the ground a bit more"
7.1	Collaborative	In 1952 Dr. Lawson was leading the team developing the X-band Klystron.
7.2.4 & 7.6	Good critic	He became renowned for his ability to "assess new concepts which people put forward" and by his own (modest) estimation was, "a good critic, really." [168]
7.2.7	Independent	"I was rather a timid person,...I was a bit of a 'loner' in my research."[169] "I was left more or less free lance [at the RAL], and much of the work I did was in looking at new ideas which were always coming along...which I was good at"[170]
7.2.7 & 7.2.8	Wanderer	"I've been a wanderer" meandering through many fields in physics; "having been wandering around a lot from one thing to another over the years, I've collected a fairly broad sort of view point on things." [171]
7.3.8	Generalist	"I used to say that I was a 'jack of all trades and master of one'." [172]
7.4	Synthesizer	It is said of Dr. Lawson that: "Though making significant contributions in many specific areas of accelerator physics, perhaps his most notable achievements have resulted from his ability to survey, in both breadth and depth, the underlying theoretical principles of the science, identify where gaps appear in the theory, and to fill them." [173]
7.4	Translator	"... I used to regard myself as a **translator**..." [174] [between different languages, notations, conventions, ideas etc. in physics]

Table 7. 1: Summary of points made throughout this chapter about Dr. Lawson's thinking style.

[166] Dr. Lawson, in his March 2003 letter to me.
[167] Dr. Lawson, in his 24-Feb-2004 letter to me.
[168] Dr. Lawson, during our telephone conversation of 22-March-2004
[169] Dr. Lawson, during our interview at his residence, 15-January-2004
[170] Dr. Lawson during our telephone conversation of 13-01-2005
[171] Dr. Lawson, during our interview at his residence, 15-January-2004
[172] Dr. Lawson, during our telephone conversation of 22-March-2004
[173] Rutherford Appleton Laboratory, Bulletin number 5, 6-April- 988
[174] Dr. Lawson, during our telephone conversation of 22-March-2004

Discussed in section	**Characteristic**	**Example from analysis of 30 of his scientific papers, his book and personal correspondence we carried out.**
7.6 And examples in appendix section A7.3 -A7.5	Preference for visual and aural structure (in science, art, music, poetry etc.)	"I enjoy things that are **structured.**" [175] This may have facilitated his own noticing of analogies and his ability to communicate these analogies to others through e.g. visual matrices which facilitate mappings between systems.
Briefly in 7.3-7.5 and in more detail in 8.5-8.7	Enthusiast for analogy	Used analogy to create mental pictures, illumination, acquire physical insight, pictorial insight, etc.
		Used analogy to facilitate communications between workers in different subdivisions of the field

Table 7.2: Summary of points made during this chapter about Dr. Lawson's thinking style.

As I have shown in section 7.6, Dr. Lawson often provided his journal readers with clear and concise summaries of the similarities between systems by creating ordered tables of sketches, mathematical equations etc. I argue that arranging information in this highly structured visual manner facilitates cross-comparison between analogous systems. His preference for this structured and visual form of representation may indicate a cognitive relation to analogical reasoning, since some cognitive scientists' (e.g. Gentner, 1989) argue that analogy involves a type of 'structure mapping' between source and target domains on a cognitive level. The fact that such 'analogy tables' are reasonably common in physics and engineering textbooks does not detract from their importance. In fact, I would argue that they are popular because they are an effective means of displaying such abstract information. The juxtaposition of abstract features and representations allows one to notice similarities and explore how far the analogies extend.

Of course analogies are **expressed differently** depending on their **function.** For example, one could present Prof. Coleman's Dazed Chicken Model (featured in chapter 6) in an 'analogy table' rather than a sketch (see table 7.3 on the next page). This structured mode of representation communicates all the key concepts of the Dazed Chicken Model and could be used to see how far the analogy extends. However, it does not have the same impact from a rhetorical perspective. It is not as memorable, entertaining or witty as Prof. Coleman's highly original, (and admittedly absurd), *Dazed Chicken Model.* Part of the effectiveness of Prof. Coleman's sketch may be related to the fact that humans tend to assimilate information better from (humorous) pictures and narratives. Memory champions

[175] Dr. Lawson, during our telephone conversation, 12:00-12:30, 22-March-2004

often use the 'method of loci' mnemonic, a memory strategy (used by ancient rhetoricians and orators) that involves imagining items placed along a route in a conceptual space, thereby combining visual and narrative modes of thought.

Table 7.3: An analogy table created from Prof. Coleman's Dazed Chicken Model sketch.

Imagine a ravine	analogous to	a potential well in which positrons can be trapped near a solid surface.
On one side of the ravine is a forest of evenly spaced trees	analogous to	a crystal lattice
Some of the trees have been up-rooted, leaving holes in the ground	analogous to	vacancies or defects in the lattice
On the other side of the ravine, chickens arc fired from a cannon	analogous to	positrons fired from a particle accelerator
The chickens get propelled across the ravine, smashing into the evenly spaced trees.	analogous to	Positrons colliding with crystal lattice
Some stagger around on the ground, completely dazed	analogous to	to thermal positron diffusion
Some fall into holes in the ground	analogous to	trapping by vacancies or defects beneath the surface
Some fall into the ravine	analogous to	surface state trapping
Some, not so dazed, fly back across the ravine	analogous to	positron re-emission

Thus, the **function** of an analogy is vitally important: Prof. Coleman's *Dazed Chicken* sketch is intended to express physics in a playful manner, to entertain, educate or inform. Prof. Coleman doodled it to pass the time at a 'far from interesting' conference talk. Later, when his colleagues found it witty and amusing, he decided to use it to good effect to promote positron physics to prospective students and the public. In fact, Prof. Coleman's sketch is somewhat like Dr. Lawson's sketch regarding a group of engineers' attempts to reach the moon (see figure 7.2). The primary function of both is to express something in a playful, entertaining and memorable way, rather than to juxtapose abstract features or representations in order to uncover similarities (as Dr. Lawson does in his waveguides and wave mechanics paper). When analogies are properly tailored to the context of use they have the power to educate, inform and entertain audiences of experts, intermediates and novices. As discussed in chapter 6, I strongly believe that a databank of good analogies, suggested by scientists with practical experience of actually 'doing' science, and a flair for communicating with experts and novices (through equations, narratives, sketches, physical models etc.) would be useful for science educators. There is a wealth of expertise within the physics and engineering community which could be tapped. Dr. Lawson's effective use of analogy to conceptualise and communicate physics will be discussed in more detail in chapter 8.

Chapter 8

On bridging conceptual divides between 'sub-cultures' of physicists and engineers: An historical case study.

"...languages and notations differ; people brought up in plasma physics, microwave tube and accelerator environments tend to use different descriptions and different groupings of fundamental constants...and we suffer from the same problems that trouble the workers on that notoriously unsuccessful project, the tower of Babel." [176]

Figure 8.1: "The Tower of Babel" by Pieter Brueghal the Elder

[176] Dr. Lawson writes on page 1 of *"Diversity and unity in sources and beams,"* published in the proceedings of a symposium on **Ion Sources and formation of Ion Beams**, held at Brookhaven in 1971.

8.0 Overview:

This chapter explores the techniques used to bridge conceptual divides between scientific communities of practice. It is based on an historical case study of Dr. Lawson, a retired engineer-physicist who frequently took on the role of 'translator' at physics-engineering workshops and conferences in the 1960s, 70s and 80s. The data stems from a content analysis of 35 of his scientific papers (1946-1997), his book on the physics of charged particle beams (1988, 2nd edition), and personal correspondence and semi-structured interviews which we carried out sporadically between 2003 and 2005. I address the following research questions:

Visualization:

- To what extent did Dr. Lawson experience difficulties getting a mental picture of the physical processes in his research?
- What reasons were given by Dr. Lawson for having/(not having) difficulties?

The use of Analogy to provide insights when conceptualising and communicating physics:

- To what extent did Dr. Lawson use analogy to acquire and promote (physical and pictorial) insight?
- What does the term "insight" mean to Dr. Lawson?
- How does **physical** insight differ from **pictorial** insight in Dr. Lawson's view?
- To what extent did Dr. Lawson use analogy to bridge sub-disciplinary divides?
- What types of analogies did Dr. Lawson employ in this context? I.e. were they physical, pictorial or mathematical, utilising within domain or between domain mappings?

In this chapter, I will show that Dr. Lawson employed mathematical, physical and pictorial analogies to great effect to provide his colleagues with physical and pictorial insights, thereby bridging conceptual divides which existed at the time between sub-disciplines in his research area.

8.1 Public and Interdisciplinary Communication: Bridging the Gulf

In her book *Science as Salvation (1992:2002)*, the philosopher, Mary Midgley addresses the problems surrounding interdisciplinary and public communication. She bemoans the fact that, "as in the Tower of Babel, each discipline speaks only in its own tongue." Yet she recognises that "there are bold and clear-headed explainers" who manage to cross the 'linguistic' divides. Midgley argues that such work:

> "is surely of first importance, since intellectual enquiries, like nation states, always do have outside relations which can matter greatly to them. They all draw concepts, presuppositions, and metaphors from outside their borders, items which can deeply affect their inner workings." (Midgley, 1992:2002, p.2).

Renowned "bold and clear-headed explainers" include scientists like Richard Dawkins, Stephen Jay Gould, Brian Greene, and Paul Davies. Some of their books have not only become best sellers throughout the world, but have been debated in the public sphere. These practicing scientists are part of what John Brockman has termed the 'Third Culture'. In the introduction to **The Third Culture: Beyond the Scientific Revolution,** (a collection of essays by scientists with a flair for communication with the public) Brockman (1995) explains that:

> "the Third Culture consists of those scientists and other thinkers in the empirical world who, through their work and expository writing, are taking the place of the traditional intellectual in rendering visible the deeper meanings of our lives, redefining who and what we are."

Brockman's term 'Third Culture' refers back to C.P. Snow's books **The Two Cultures** (1959) and the **Two Cultures: A Second Look** (1963). In the first edition, Snow was concerned by the "gulf of mutual incomprehension" (Snow, 1959, p.4) that separated literary intellectuals and scientists.[177] In the second edition, Snow was more optimistic, believing that a *Third Culture* was emerging, consisting of scientists and literary intellectuals who were beginning to bridge the gulf of incomprehension. Brockman's 'third culture' differs from the 'third culture' predicted by Snow because in Brockman's third culture, scientists communicate directly with the public, not via the literary intellectuals.

While it is widely accepted that 'gulfs of mutual incomprehension' can exist between scientists and the public, it is less widely known that mini gulfs can also exist between sub-cultures of specialist scientists. As discussed in previous chapters, there are 'cultural' differences between engineers, mathematicians, theoretical physicists, experimental

[177] Incidentally, Dr. Lawson was interviewed by C.P. Snow during the war, to decide whether he should be sent to the armed services, industry, or research. The board sent Dr. Lawson to the Telecommunications Research Establishment (TRE).

physicists, computational physicists etc. For example, Bissell and Dillon (practicing engineers) tell us that:

> "The aims and purposes of engineers are not those of mathematicians. There is a focus on explanation and design, in contrast to mathematical structure and rigour... [T]raditions of explanations are different in different domains: what counts as an acceptable mathematical argument is unlikely to count as an acceptable engineering argument... [D]ifferent communities of practice lead to different ways of talking and doing, even when they are apparently dealing with the 'same thing'. Tacit skills learnt by experience in engineering may not integrate well with the formal skills laid down in mathematics courses." (Bissell & Dillon, 2000, p.10)

Thus, even within physics, sub-fields such as microwave tube, accelerator or plasma physics form 'sub-cultures' of physicists who utilise different mathematical notations, groupings of fundamental constants, codes (i.e. syntax and jargon) etc. By limiting vocabulary & flexibility, these codes transmit culture, designate group solidarity, and facilitate communication within 'sub-cultures' (cf. Henderson, 1995, p.211-212). This specialization is necessary and desirable given the aims of a sub-field. However, when attempting to tackle a larger, more complex version of a problem, requiring collaboration between subfields, this plurality of 'languages'can sometimes impede communication of ideas between 'sub-cultures'. [178]

Dr. Lawson highlighted the issue of restricted codes during a talk on *Ion Sources and formation of Ion Beams* at a symposium in Brookhaven in 1971. He noted that: "... languages and notations differ; people brought up in plasma physics, microwave tube and accelerator environments tend to use different descriptions and different groupings of fundamental constants... " (Lawson, 1971, p.1).[179] Such 'sub-cultural' differences can inhibit communication on a project requiring collaboration between physicists and engineers working in different fields because, as Dr. Lawson explains in the same paper: "Particular languages develop, and we suffer from the same problems that trouble the workers on that notoriously unsuccessful project, the tower of Babel" (ibid.). During our telephone conversation of 22-03-2004, Dr Lawson was keen to emphasise that: "it's more

[178] This is reminiscent of the biblical story of the Tower of Babel (Genesis chapter 11) which describes how, in an attempt to reach the heavens, humanity (united and mono-lingual) began construction on the Tower of Babel. To confuse the workers and prevent their project from proceeding, God introduced a plurality of languages. The workers, now speaking different languages, could not communicate with one another and the project ultimately collapsed.

[179] "...a plasma physicists naturally thinks of the transverse temperature and pressure of a beam, whereas an accelerator physicist sees it in terms of the emittance and focusing strengths. Space charge effects can be seen in terms of perveance, Laslett Q-shifts, or a non-zero effective plasma frequency. Beams can be characterised by volts and amps, or by number densities, radii and drift velocities" Dr. Lawson, in "Diversity and unity in sources and beams," (Lawson, 1971, p.1)

than just the 'language', it's the actual formulation of the theory. So it isn't so obvious sometimes that people are talking about the same thing, because they have thought of it differently." I often think that Babel fish[180] would be extremely useful at interdisciplinary conferences where sub-cultures of physicists and engineers exchange ideas. Unfortunately, these biological universal translators are exceedingly difficult to catch (being entirely fictitious). So, without the aid of Babel fish, how do physicists dismantle boundaries and bridge 'linguistic' divides between sub-cultures of the physics community?

8.2 If You Can't Catch A Babel Fish Try A Using A Pidgin.

As the sociologist of science Peter Galison remarks, when an H-bomb designer, a logician, an aero-dynamical engineer, and a statistician sit down together, they do not don head-phones and communicate through interpreters, League of Nations style. According to Galison, "they work out an intermediate language, a pidgin, that serves a local, mediating capacity." (Galison & Stump, 1996, p14). But how exactly do they do this? What form does this new pidgin language take?

Henderson's ethnographic studies of the visual culture of engineers reveal that, "[t]o participate at all in the engineering design process actors must engage one another through the visual representation of the conscription device." (Henderson, 1995, p.214-215). A subgroup of inscription devices, *conscription devices* "enlist group participation and are receptacles of knowledge created and adjusted through group interaction with a common goal." (Ibid.). As these conscription devices mean different things to the various actors who employ them (e.g. designers and managers) they serve as *boundary objects*. According to Star, "boundary objects" are: "plastic enough to adapt to local needs and constraints of the several parties employing them, yet robust enough to maintain a common identity across sites." (Star, 1989, p. 298, see also, Bowker & Star, 1999). Gorman (2005, p.292) notes that, "boundary objects will be absent from trading zones that are dominated by an elite group but are likely to exist in trading zones where the partners are relatively equal." The term *trading zone* was coined by Galison. According to Galison, the trading zone is "the site – partly symbolic and partly spatial – at which the local coordination between beliefs and action takes place." (Galison, 1997, p.784)

[180] Fans of Douglas Adams' science fiction classic, "The Hitch Hiker's Guide to the Galaxy" will know that Babel fish are highly improbable biological universal translators. A "small, yellow and leech-like… " fish which "… feeds on the brainwave energy received…from those around it… " So that "… if you stick a Babel fish in your ear you can instantly understand anything said to you in any form of language." (Adams, 1979:1995, H2G2, p. 52)

Conscription devices and boundary objects share commonalities with what Gooding refers to as "*construals*". When negotiating consensus about what they are seeing, Gooding says:

> "Observers construe and reconstrue their own experience in the light of what other observers take theirs to be. Construals are a means of interpreting unfamiliar experience and communicating one's trial interpretations. Construals are practical, situational and often concrete. They belong to the pre-verbal context of ostensive practices." (Gooding, 1990, p.23)

I would argue that **analogies** are a type of *boundary object*: the analogy highlights certain features which two systems share which can then be explored in further depth. The core of the theory under discussion remains invariant. Analogies are also a type of *construal*: by drawing comparisons to pre-existing experiential and abstract knowledge, experts (and for that matter most people) use analogies to shed light on unfamiliar territories. This happens in private conceptualisation when scientists are problem solving in solitude but also within so-called trading zones, where experts exchange ideas on their respective areas of research. According to Gorman: "... tacit representations are frequent sources of misunderstandings in multidisciplinary trading zones." (Gorman, 2005, p.293). Gorman's comments are borne out by Dr. Lawson's experiences. In the latter part of his career, Dr. Lawson said he:

> "attended numerous workshops on emerging concepts and ideas, where there was plenty of controversy and argument; I noted particularly how those with different backgrounds and different nationalities had different ways of thinking about things. (For example 'why does this effect occur?' – 1) 'because the direction of flow has changed' 2) 'because the third term in the equation is now larger than the second' – both true but not necessarily clear to all parties!" [181]

I will now discuss the particular techniques employed by Dr. Lawson to conceptualise and communicate his research.

[181] Dr. Lawson, in his March 2003 letter to Ciara Muldoon.

8.3 Conceptualisation & Communication Techniques Used by Dr. Lawson in his Work.

In a paper entitled, *"Telling Tales: Models, Stories and Meanings"*, Bissell and Dillon (2000, p.6) note that: "… the engineering emphasis is not on solving the equations at all, but in gaining insight about the system." They explain that:

> "Over the years, practicing engineers have developed a range of ingenious tools, techniques and insights to move them away from having to deal with the mathematics directly. While the language of mathematics focuses on 'solving equations', engineering techniques often focus on interpretative understanding of graphical representations of the same information." (ibid. p.10)

Dr. Lawson's first degree was in mechanical sciences. Thus it is not surprising that to gain insight, Dr. Lawson frequently used techniques such as simplification, limiting case analysis, graphical representations of data and analogical reasoning. For example, during our first interview, Dr. Lawson explained his general approach to problem solving, saying:

> "Often, I think, it's better to go back to the physics, and look at the essentials, and in fact, solve a problem that is easier than the one that we want to solve but it's the same nature… I'm not one for emphasising rigour in the early development stages of a subject. In fact, I think the more we keep away from rigour, the better it is. And this joke about a calculation… 'assume a spherical elephant'… well, I would approve of that…Very often you can see, rather simply, that this is not a profitable way of going… " (Dr. Lawson, during an interview of 15-01-2004).

Such techniques are typical of physicists and engineers. In fact, the 'assume a spherical elephant' approach to problem solving has become **stereotypical** of physicists and engineers! This point is made in the following humorous anecdote (attributed to Adam Katalsky, **New Scientist**, 19-26 December 1992) shown on the following page. [182]

[182] It was quoted by David Gooding at a workshop on Cognitive Studies of Science and Technology that was held at the University of Virginia in March 2001, in order to highlight the different disciplinary approaches of researchers in this area. It appears in Gorman, Tweney, Gooding, & Kincannon, (eds), 2005, p.2

A millionaire with a passion for horse racing offered a large prize -- enough to buy a few Silicon Graphics machines -- to anyone who could predict the outcome of any horse race. Three scientists took up the challenge, a physiologist, a geneticist and a theoretical physicist. One year later the three scientists announced their results. Here's what each reported:

The Physiologist: "I have analysed oxygen uptake, power to weight ratios, dietary intake and metabolic rates, but there are just too many variables. I am unable to predict which horse will win."

The Geneticist: "I have examined blood lines, breeding programs and all the form books, but there are just too many uncertainties. I cannot predict who will win any race".

The Physicist: "I have developed a theoretical model of the dynamics of horse racing, and have used it to write a computer program that will predict the outcome of any horse race to 7 decimal places. I claim the prize. But -- there is one proviso. The model is only valid for a perfectly spherical horse moving through a vacuum"

Although Dr. Lawson often used problem solving techniques characteristic of physicists and engineers, I believe it is necessary to explore the value he placed on using particular techniques in particular contexts, e.g. in private conceptualisation and when communicating with experts and intermediates.

In his introductory letter to me (of March 2003), Dr. Lawson explained: "I am great enthusiast for analogies since I think pictorially and not mathematically." In our second interview, when asked to comment, from his recollections, on the tools, techniques and problem solving strategies that he used in his work, Dr. Lawson replied:

> "... Often if there's a complicated problem that you don't quite know how to tackle, the thing is to **invent** a simpler problem of the same class, which you think you can tackle. And then that'll perhaps give you some **insights** into the overall problem that you can look at it again and decide on your strategy... " (Dr. Lawson during our telephone conversation of 22-03-2204)

Thus, having carried out a detailed analysis of a large faction of Dr. Lawson's work, I have concluded that Dr. Lawson often used **analogy** to acquire insights in private conceptualisation. He also used analogy in a second context: to provide his colleagues with insights and thereby facilitate communication between sub-cultures of physicists and engineers. In fact he told me: "... I used to regard myself as a translator... " [183] of 'languages', notations and ideas at physics workshops and conferences. As mentioned in chapter 7, Dr. Lawson drew analogies between many sub-fields in order to provide a synthesis of perspectives. For example, in the conclusion of one paper, where he draws analogy between an ion beam and a drifting gas, he says:

> "A synthesis of viewpoints deriving from optics, thermodynamics and hydrodynamics has been demonstrated... Such interdisciplinary viewpoints are valuable, first in providing an insight into the essential nature and behaviour of beams, and second, particularly in the field of very intense and ring beams, in facilitating communications between workers in different subdivisions of this varied and fascinating field." (Lawson, J.D., 1978, p.222)

By providing a synthesis of viewpoints, Dr. Lawson enables researchers to reconcile their differing perspectives, and thereby achieve a richer understanding of the nature of the topic being investigated. This is analogous to Gruber and Shel's shadow box experiment. (Gruber, 1985). Here observers see a different projection of an object in a box. One sees a triangle, the other a circle. Initially each doubts the accuracy of the other's observations and challenges the other's competence. After clarifying communications, they reconcile their differences through the realisation that the object in the shadow box is in fact a cone: the base of the cone is projected as a circle on one side of the shadow box, while the curved side of the cone is projected as a planar triangle on the other side of the shadow box. The key point is that without the ability to communicate their different perspectives – to say, "I see a triangle, what do you see?" "I see a circle. Are you sure it's a triangle? Describe what it looks like" - they would not be able to reach a consensus and deduce that their conflicting observations were merely different perspectives. By using analogy and synthesis, Dr. Lawson acts as 'translator', facilitating communications between workers who 'see' things from a different perspective.

The concern with presenting scientific material to individuals having different modes of thought is not a new thing. In his address to the British Association in September 1870, Maxwell remarked upon the contrasting modes of thought amongst his contemporaries. On the one hand, he said, there are:

> "... men who, when any relation or law, however complex, is put before them in a symbolical form, can grasp its full meaning as a relation among abstract quantities. Such men sometimes treat with indifference the further statement that quantities actually exist in nature which fulfil this relation. The mental image of the concrete reality seems rather to disturb them." (Maxwell, 1890, p. 220)

[183] Dr. Lawson, during our telephone conversation on 22-March-2004

On the other hand, there are:

> "… others who feel more enjoyment in following geometrical forms, which they draw on paper, or build up in the empty space before them. Others again, are not content unless they can project their whole physical energies in to the scene which they conjure up. They learn at what a rate the planets rush through space, and they experience a delightful feeling of exhilaration. They calculate the forces with which the heavenly bodies pull at one another and they feel their own muscles straining with the effort.." (ibid.)

Maxwell suggested that:

> "… for the sake of persons of these different types, scientific truth should be presented in different forms, and should be regarded as equally scientific, whether it appears in the robust form and the vivid colouring of a physical illustration, or in the tenuity and paleness of symbolical expression." (ibid.)

As mentioned in sections 3.6 and 4.10, the approach proposed by Maxwell is frequently adopted by Prof. Berry in his papers, with positive results.

A range of instances in which Dr. Lawson uses analogy and synthesis to acquire insight and bridge divides between sub-fields of physics and engineering is presented in tables 8.1a, 8.1b, 8.2a and 8.2b. They are derived from analysis of 30 of his scientific papers and his book on *"The Physics of Charged Particle Beams"* and presented chronologically, from 1950 to 1989. Highlighted and italicised text is derived from post-it note annotations which Dr. Lawson made on papers enclosed in his March 2003 letter to me. As tables 8.1a&b, 8.2a&b indicate, Dr. Lawson's notion of insight has some specific associated concepts: pictorial insight, illumination, physical insight, getting a feel for something, physical pictures, physical points of view, etc. This issue is discussed further in sections 8.4 and 8.5.

ID	Title of paper	Use of analogy to acquire physical insight
1.	Wave Guides and Wave Mechanics: Some Similarities and Differences (1950)	"An understanding of a simple system may help one to acquire some insight into a more complicated or subtle system."
2.	Čherenkov Radiation 'Physical' and 'Unphysical', and its Relation to Radiation from an Accelerated Electron (1965)	"The value of this treatment lies in the insight which it gives into radiation phenomena; it adds nothing to the already adequate techniques for solving specific problems." "The physical picture is quite clear, as βn decreases through unity the Čherenkov radiation suddenly becomes unphysical, in just the same way as a refracted ray at the critical angle."
3.	Analogous Behaviour of Elementary Particles And Some Simple Waveguide and Cavity Systems. (1965)	"Although it is not profitable to look for precise parallels to particular systems of elementary particles, some physical insight into the behaviour of these particles may nevertheless be obtained." "Although these analogies are essentially trivial, they are very striking and enable the non-specialist to get a 'feel' for the way that elementary particles behave, in terms of well-known systems which are completely understood." "Analogies in which this correspondence is made are more restrictive in some respects but more illuminating in others."
4.	Some Attributes of Real and Virtual Photons (1970)	"an attempt is made to discuss some basic properties of photons from a physical point of view…" "The calculation, which can generally be performed in several different ways, must be viewed as a whole; it is not possible in principle to make a measurement which gives a picture of what is 'actually happening' in a classical sense during the process." "with the object of giving a more physical and pictorial insight of the actual classical field structure (in terms familiar, for example, to a radio engineer), and further, of removing possible confusion between the two pictures."

Table 8.1a: Excerpts from Dr. Lawson's scientific papers and book highlighting his use of analogy to provide physical insight to experts in the fields of applied optics, plasma physics, nuclear physics, high energy and particle physics and astrophysics.

ID	Title of paper	Use of analogy to acquire physical insight
5.	The Ion Beam as a Drifting Gas (1978)	"A synthesis of viewpoints deriving from optics, thermodynamics and hydrodynamics has been demonstrated....Such interdisciplinary viewpoints are valuable, first in providing an insight into the essential nature and behaviour of beams, and second, particularly in the field of very intense and ring beams, in facilitating communications between workers in different subdivisions of this varied and fascinating field."
6.	Particle-Photon Interactions (1989)	"...a consideration of the interaction between particles and fields in terms of photons, which may be virtual or real, does provide some interesting insights." "...a physical description based on the correspondence between energy and frequency, and between momentum and wavelength, does yield some interesting insights." "This paper is concerned not with presenting techniques for making calculations or solving problems, but rather introducing a physical viewpoint which enables the relation between a range of different phenomena to be seen." "An important feature has been an attempt to show that a discussion in terms of photons of topics normally treated classically can give new and perhaps helpful insights."
7.	***The Physics of Charged Particle Beams. (1988, 2nd Ed.)***	"Although some of the situations to be analysed are of little direct practical interest, they can be instructive in giving insights into the behaviour of more complex realistic systems." (p.104) "the detailed behaviour of diodes and beams can only be studied by experiment and sophisticated computer modelling, though, of course, an analysis of idealized and simplified physical situations can often provide valuable insights." (p113)

Table 8.1b: Excerpts from Dr. Lawson's scientific papers and book highlighting his use of analogy to provide physical insight to experts in the fields of applied optics, plasma physics, nuclear physics, high energy and particle physics and astrophysics.

ID	Title of paper	Use of analogy and synthesis to bridge sub-disciplinary boundaries in physics and engineering.
i	Note on the Angular Distribution of Radiation from Fairly Thin Targets Bombarded by High Energy Electrons (1952)	"At least four papers have appeared in recent years in which a calculation is made of the angular distribution of bremsstrahlung from targets sufficiently thin that ionisation loss and straggling are negligible but sufficiently thick that multiple scattering of the electrons is important…In no two of these is the expression obtained for the angular distribution the same, nor have the method of derivation and approximations used in the calculations always been clearly stated. This note is intended to clarify the position, by showing that there are two essentially different ways of carrying out the analysis, which lead to slightly different results."
ii	On the classification of electron streams (1959)	*"This paper uses a notation that allows a number of different technical applications to be integrated."*
iii /2	Čherenkov Radiation 'Physical' and 'Unphysical', and its Relation to Radiation from an Accelerated Electron (1965)	"The differences between Čherenkov radiation and bremsstrahlung are often emphasized; the unified treatment in this paper in which physical and unphysical phenomena are treated on an equal footing will perhaps be helpful in showing that there is a link between them." "This type of unification may be applied to other types of phenomena; the industrious reader will soon convince himself for example that a proton linear accelerator is an unphysical diffraction grating."
iv	Diversity and Unity in Sources and Beams (1971)	"…languages and notations differ; people brought up in plasma physics, microwave tube and accelerator environments tend to use different descriptions and different groupings of fundamental constants..." "Particular languages develop, and we suffer from the same problems that trouble the workers on that notoriously unsuccessful project, the tower of Babel." "our concern is with unification, and we shall quote the equation in what is intended to be its simplest and most universal form." "what I have done is merely to collect together and display as a single exhibit a number of well tried old approaches."

Table 8.2a: Examples from Dr. Lawson's scientific papers and book highlighting his use of analogy and synthesis to bridge sub-disciplinary boundaries in the fields of applied optics, plasma physics, nuclear physics, high energy and particle physics and astrophysics.

ID	Title of paper	Dr. Lawson's use of analogy and synthesis to bridge sub-disciplinary boundaries in physics and engineering.
A	Emittance, Entropy And Information (1973)	*"Again concepts in different fields are fundamentally related."*
B	Optical and hydrodynamical approaches to charged particle beams (1975)	*"not an analogue, but two different view points – which enable a richer appreciation of the field to be obtained."*
C /5	The Ion Beam as a Drifting Gas (1978)	"A synthesis of viewpoints deriving from optics, thermodynamics and hydrodynamics has been demonstrated….Such interdisciplinary viewpoints are valuable, first in providing an insight into the essential nature and behaviour of beams, and second, particularly in the field of very intense and ring beams, in facilitating communications between workers in different subdivisions of this varied and fascinating field."
D	Lasers and Accelerators (1979)	*"Again – showing common features in two quite different technical devices."*
E	A synthetic approach to some electromagnetic wave phenomena (1984)	"In this paper a unified viewpoint is sketched, the object of which is to show how a few underlying physical features are common to a number of phenomena which may not appear at first sight to be closely related. The aim is to present unifying physical insights rather than methods for solving problems, and to supplement rather than replace existing points of view." "Although its value in enabling detailed calculations to be made is limited, it can be of help in conceptual thinking which helps to classify and relate together quite a wide range of electromagnetic wave problems of practical interest."
G /6	*Particle-Photon Interactions (1989)*	*"Again a wide range of phenomena looked at from a simple common viewpoint. (I was challenged to write a similar paper with only one equation!…"*
F /7	**The Physics of Charged Particle Beams (1988, 2nd Ed)**	"In this monograph, the unity of things encountered in different contexts is emphasised and classification is in terms of physical features rather than application. A wide range of topics is surveyed…The approach is synthetic; simple examples are considered first, and the complications introduced gradually."

Table 8.2b: Examples from Dr. Lawson's scientific papers and book highlighting his use of analogy and synthesis to bridge sub-disciplinary boundaries in the fields of applied optics, plasma physics, nuclear physics, high energy and particle physics and astrophysics.

8.4 Discussion of Examples from Dr. Lawson's scientific papers and book highlighting his use of Analogy & Synthesis to Provide Insights

An example of Dr. Lawson's use of analogy to provide physical and/or pictorial insight is illustrated in my figure 8.2, on the next page. The image, taken from his book on *The Physics of Charged Particle Beams,* shows two figures from Dr. Lawson's book. In his figure 2.24 a biased pendulum provides an analogue of phase oscillations; and in his figure 2.25 he uses a 'wavy-slope' analogue of phase motion, with particles being analogous to balls. Note that Dr. Lawson's figures 2.24 and 2.25 are different types of representation: figure 2.24 is a depiction (depicting something that Dr. Lawson could have had experience of directly observing with the naked eye, and directly manipulating with his hands), while figure 2.25 is a symbolic representation of figure 2.24. When questioned in a follow-up letter, Dr. Lawson said he drew these figures himself, adding that: "Pictures similar to 2.24 appear elsewhere. I don't remember seeing fig 2.25 but it may be somewhere." Recall from section Goodman's (1976, p.171) remarks that, "The mere presence or absence of letters or figures does not make the difference. What matters with a diagram, as with the face of an instrument, is how we are to read it." Reading diagrams or labelled images involves the recognition of certain conventions that are learned as one requires expertise in the field. This example of analogy would fit within set C of my venn diagram (section 5.5). The analogies have mathematical, physical and pictorial components. They have considerable systematicity, holding for a hierarchy of relations. They are intended to be useful for experts and intermediates. Note that intermediates may be third level students who are new to the discipline as a whole, or they may be researchers who have expertise in one branch of physics or engineering (e.g. optics) but not in another (e.g. plasma physics). In fact, Dr. Lawson said in the preface of the first edition of this book that although there exist many books which separately cover such subjects as electron optics, microwave tubes, particle accelerators, and plasma physics, his work is "perhaps unique in bringing together material from all these fields." (1977, p. vii) His primary goal in his book & scientific papers is to bring diverse viewpoints together in order to facilitate cross-fertilisation of ideas. (See especially table 8.2a, examples i and iv, and table 8.2b examples C and E).

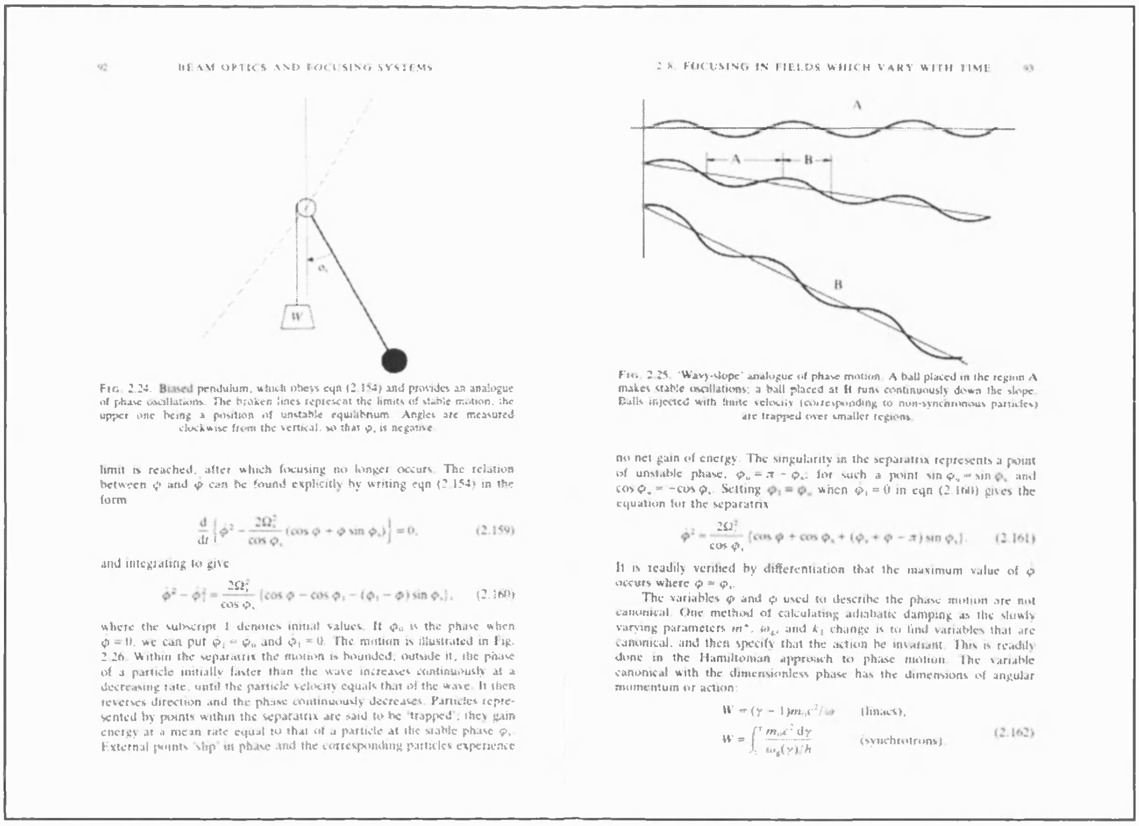

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FIG. 2.24. Biased pendulum, which obeys eqn (2.154) and provides an analogue of phase oscillations. The broken lines represent the limits of stable motion, the upper one being a position of unstable equilibrium. Angles are measured clockwise from the vertical, so that φ_s is negative.

limit is reached, after which focusing no longer occurs. The relation between $\dot{\varphi}$ and φ can be found explicitly by writing eqn (2.154) in the form

$$\frac{d}{dt}\left\{\dot{\varphi}^2 - \frac{2\Omega_s^2}{\cos\varphi_s}(\cos\varphi + \varphi\sin\varphi_s)\right\} = 0, \qquad (2.159)$$

and integrating to give

$$\dot{\varphi}^2 - \dot{\varphi}_i^2 = \frac{2\Omega_s^2}{\cos\varphi_s}\{\cos\varphi - \cos\varphi_i - (\varphi_i - \varphi)\sin\varphi_s\}, \qquad (2.160)$$

where the subscript i denotes initial values. If φ_0 is the phase when $\dot{\varphi} = 0$, we can put $\varphi_i = \varphi_0$ and $\dot{\varphi}_i = 0$. The motion is illustrated in Fig. 2.26. Within the separatrix the motion is bounded; outside it, the phase of a particle initially faster than the wave increases continuously at a decreasing rate, until the particle velocity equals that of the wave. It then reverses direction and the phase continuously decreases. Particles represented by points within the separatrix are said to be 'trapped'; they gain energy at a mean rate equal to that of a particle at the stable phase φ_s. External points 'slip' in phase and the corresponding particles experience

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FIG. 2.25. 'Wavy-slope' analogue of phase motion. A ball placed in the region A makes stable oscillations; a ball placed at B runs continuously down the slope. Balls injected with finite velocity (corresponding to non-synchronous particles) are trapped over smaller regions.

no net gain of energy. The singularity in the separatrix represents a point of unstable phase, $\varphi_u = \pi - \varphi_s$; for such a point $\sin\varphi_u = \sin\varphi_s$ and $\cos\varphi_u = -\cos\varphi_s$. Setting $\varphi_i = \varphi_u$ when $\dot{\varphi}_i = 0$ in eqn (2.160) gives the equation for the separatrix

$$\dot{\varphi}^2 = \frac{2\Omega_s^2}{\cos\varphi_s}\{\cos\varphi + \cos\varphi_s + (\varphi_s + \varphi - \pi)\sin\varphi_s\}. \qquad (2.161)$$

It is readily verified by differentiation that the maximum value of $\dot{\varphi}$ occurs where $\varphi = \varphi_s$.

The variables φ and $\dot{\varphi}$ used to describe the phase motion are not canonical. One method of calculating adiabatic damping as the slowly varying parameters m^*, ω_s, and k_1 change is to find variables that are canonical, and then specify that the action be invariant. This is readily done in the Hamiltonian approach to phase motion. The variable canonical with the dimensionless phase has the dimensions of angular momentum or action:

$$W = (\gamma - 1)m_0c^2/\omega \qquad \text{(linacs)},$$
$$W = \int^{\gamma} \frac{m_0c^2\,d\gamma}{\omega_s(\gamma)/h} \qquad \text{(synchrotrons)}. \qquad (2.162)$$

Figure 8.2 Example of analogy from Dr. Lawson's book, 1989, 2nd Edition, pp. 92-93

In the accompanying text Dr. Lawson goes on to say that:

> "An even better analogue is a horizontal modulated surface in a horizontal plane accelerated at a rate $(2\pi gH/\lambda)\sin\varphi_s$, where g is the acceleration due to gravity and the wavelength λ increases adiabatically during the acceleration. The more important characteristics of the motion can be seen immediately from these analogues." (1988, p.91)

His use of the term "seen" suggests insight, illumination, clarity, visualizability etc. This fits with the popular conception that there is a sudden visual clarity associated with insight. When discussing insight we often mention flashes of insight, mental illumination, enlightenment, clarity, lucidity, picturability, seeing the solution in the minds eye, and so on. In a sense this very notion of connecting insight with visual clarity is itself an analogy. For instance, after studying the infamous scientific insights of Archimedes, Poincaré et al., René Taton wrote in 1962 that "the study of various types of invention and discovery has shown us that after a long effort of reflection and research a discovery will suddenly flash into the mind of the research worker by means of a sudden illumination, the so-called Geistesblizt." (Taton, 1962, p .74). Geistesblist is German for 'spirit lightning'. In the experience of theoretical physicist Fritjof Capra: "During these periods of relaxation after concentrated intellectual activity, the intuitive mind seems to take over and can produce the sudden, clarifying insights which give so much joy and delight to scientific research." (Capra, 1992, p.39).

In section 1.6, I discussed the importance of tacit knowledge in science, particularly experimental science which relies on fingertip knowledge when building and testing equipment. I asked to what extent does one acquire insights by incorporating culturally acquired, tacit, kinaesthetic knowledge into physical analogies. For example, Gooding (2004b) has discussed how: "Faraday's detailed records of his laboratory work show how visualisation works in conjunction with sensorimotor awareness (proprioception or kinaesthetic awareness) to produce representations whose cognitive (generative) and social (communicative) functions are inextricably linked." (Gooding, 2004b, p.7) An analysis of Dr. Lawson's scientific papers suggests that experiential, **tacit knowledge** can be an important component of **physical insight**.

For example of Dr. Laswon's use of analogy to provide physical and pictorial insights appears in a 1965 paper which deals with *"Analogous Behaviour of Elementary Particles And Some Simple Waveguide and Cavity Systems."* Here, Dr. Lawson et al emphasise that: "Although these analogies are essentially trivial, they are very striking and enable the non-specialist to get a 'feel' for the way that elementary particles behave, in terms of well-known systems which are completely understood." (See table 8.1a, #3). Lawson's comments are in line with Bissell & Dillon's comments about modelling (discussed in section 1.9). According to Bissell & Dillon, "intuition is important – successful modellers often have a surprisingly well-developed 'feel' for the type of model likely to be successful in given circumstances." (2000, p.10). One could argue that this 'feel' is not particularly surprising considering that the education of engineers and physicists includes training in how to approach problems. Kuhn (1962) said that such 'exemplars' enable scientists to see new puzzles in terms of familiar puzzles and thereby extrapolate possible solutions. In fact, this problem solving technique has become stereotypical of the physicist and engineer. As we saw with the "assume a spherical horse/cow/elephant" joke in section 8.4, the misuse of the 'exemplar' approach to problem solving is often lampooned.

Another example indicating that tacit knowledge is an important component of physical insight appears in a1970 paper, in which Dr. Lawson discusses *Some Attributes of Real and Virtual Photons*, (see table 8.1a, #4). Here, he says the objective is to give: "a more physical and pictorial insight of the actual classical field structure (in terms familiar, for example, to a radio engineer), and further, of removing possible confusion between the two pictures." (1970, p.575). Recall that Dr. Lawson's early training at TRE Malvern was as a radio engineer (see section 7.3.3). He did not have a particularly solid formal education in mathematics. He learned what he needed on the job, surrounded by some of the best physicists in the country. Although Dr. Lawson is an enthusiast for employing mathematical, physical and pictorial analogies to conceptualise and communicate physics, he is keen to highlight the limitations of analogical reasoning. In his 1965 paper which deals with *"Analogous Behaviour of Elementary Particles And Some Simple Waveguide and Cavity Systems"* he says:

> "When making analogies one must always be careful not to push them too far... It should be observed too that there are different ways in which analogies can be drawn. In this paper there is no correspondence between the spatial coordinates of the waveguides and the spatial coordinates of the elementary particles. Analogies in which this correspondence is made are more restrictive in some respects but more illuminating in others..." (Lawson, 1965, p. 738)

Thus, as discussed in 6.12, when reasoning by analogy one must push the positive analogies as far as possible and avoid being misled by the neutral and negative analogies.

The notion of getting "a 'feel' for the way that elementary particles behave" is also mentioned in Dr. Lawson's book (1988, p.351). In figure 8.3 on the next page, I show two tables from his book: table 6.3 is a symbolic representation of "transverse filamentary waves on a focused beam"; table 6.4 illustrates "transverse filamentary waves in an axial magnetic field." As you can see, Dr. Lawson sketches the rotation of the particles within a classificatory system that includes (a) direction of helix; (b) rotation frequency; (c) wave velocity; and (d) type of wave. He then deepens the physical and pictorial insight by drawing an analogy to a garden hose, noting: "these synchronous waves are similar to those obtainable from a garden hose by rotating the nozzle either in clockwise or anti-clockwise at constant frequency." (1988, p351).

Bissell and Dillon (2000, p.10) tell us that the language used by engineers "is more than just a handy way of coping with the mathematics" it "indicates a way of thinking about systems behaviour in which the features of the models are deeply linked to the systems they are describing." (ibid.) For example, they say that from the perspective of many electronic engineers: "the poles effectively cease to be just convenient visualisations of mathematical complex variable theory and become system features which are just as real as the electronic components from which the system was built." (ibid) They note that this represents a **different ontology**, where "the system poles are not simply part of convenient mathematical model, they are what *cause* the system to behave as it does, as if they had the tangible existence of the physical components and measurable signals present in a system." (ibid.) Thus from an engineering standpoint, "this language is an important way not only of representing important aspects of system's behaviour, but also of explaining how that behaviour comes about." (ibid.)

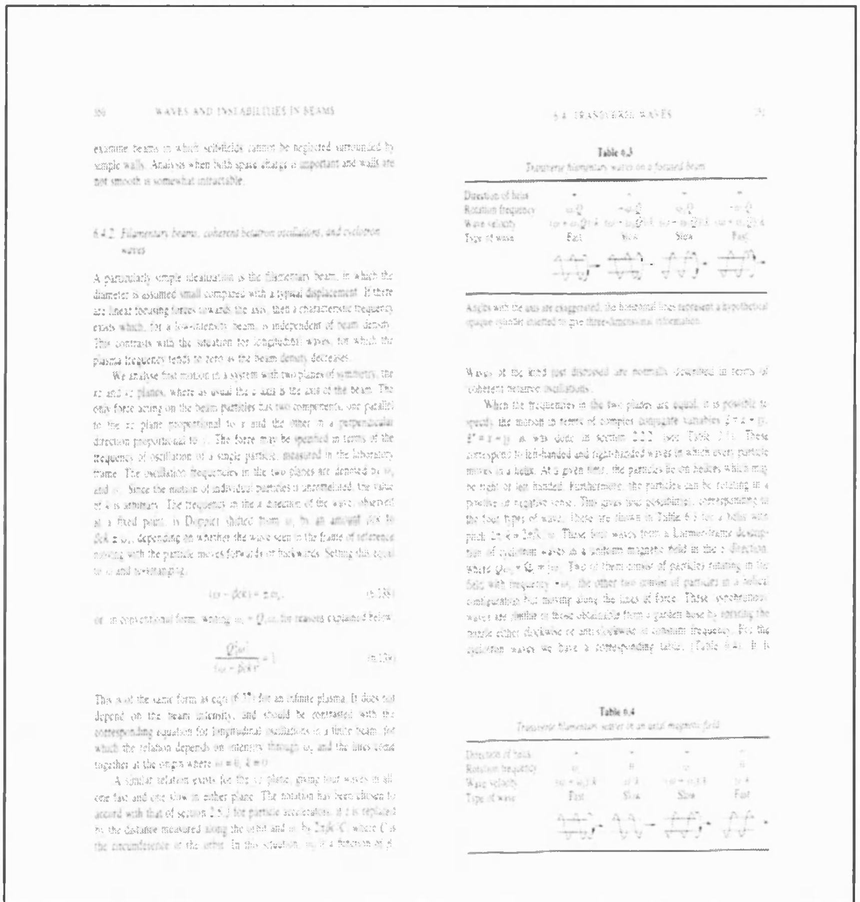

Figure 8.3: Example of physical analogy from Dr. Lawson's book, The Physics of Charged Particle Beams, 1989, 2nd Edition, pp. 350-351

The concept of 'physical insight' remains somewhat vague. How does physics insight differ from pictorial insight? Does the **tangible or tacit** facet equate with the **'physical'** while the **'illumination'** facet equates with the **'insight'**. Does acquiring insight mean achieving a 'clear view' of something, while acquiring 'physical insight' means achieving a 'clear view' plus a tacit 'feel' for something? I will address this issue in section 8.5.

8.5 How do physical & pictorial insight differ in Dr. Lawson's view?

After analysing his book and 30 of his scientific papers it was clear that Dr. Lawson attaches particular importance to gaining physical and pictorial insights in physics. But what does Dr. Lawson mean by insight, physical insight and pictorial insight? How do they differ? In what contexts did he seek to acquire only pictorial insight? In what contexts did he seek to acquire both pictorial and physical insight? To what extent does it depend on his previous experiences: on his theoretical understanding, visual memories and tactile experiences? I put these questions to Dr. Lawson in a follow-up questionnaire (on 04-10-2004). He provided me with the following definitions:

> **Insight:** "Seeing connections between two situations which are not obviously related. This helps to form a network of situations which aids new thinking."
> - (This fits the following examples: table 8.1a, #1; table 8.1b, #5, #6)
>
> **Physical Insight:** "A deeper insight than normal, suggesting relation to other physical phenomena that one understands."
> - (This fits the following examples: table 8.1a, #3).
>
> **Pictorial Insight:** "Pictorial when one visualizes the situation in such a way that there is an actual detailed picture in the mind. The two terms overlap slightly."
> - (This fits the following examples: table 8.1a, #4).

So is it possible to have physical insight without a visual representation? David Gooding believes so. He tells me that it is,

> "likely that as our verbal abilities develop, we transfer the representational 'work' from models and images onto more abstract forms, or onto language. This is how Maxwell <u>ceased</u> to rely on the mechanical models of aether, and was happy to 'think' just with the mathematics. But I suspect Thomson couldn't make this shift – so he rejected quaternions when Maxwell embraced them." (Gooding, in private communication, May 2005)

When I spoke with Dr. Lawson by telephone in March 2004, I asked him exactly what he meant by **"insight"** or **"physical insight"** in the context of his *Waveguides and Wave Mechanics* paper. Specifically, I asked Dr. Lawson whether it is "possible, to have physical insight without a visual representation, either internally (inside your head), or externally (in a sketch or something)." Dr. Lawson responded saying:

> "Yes, well, I don't know. I suppose in quantum theory - - I've always found High Energy Physics and these mathematical things which rely on starting off with Lagrangians and things of this sort - - which is of course the formal way to do it - - but since I never was educated in that direction, I always find this sort of thing difficult and so I have to invent my own way of thinking about particular problems. Just seeing how certain problems seem to be related in one way or another." (Dr. Lawson, by phone, 22-03-2004).

This refers back to Dr. Lawson's holistic or big-picture tendencies and his skills at synthesising and unifying disparate areas of research and presenting his colleagues with a more unified view. From the above examples, one could argue that Dr. Lawson's approach was in some ways similar to Faraday's: for both men, intelligibility of a process equated with *'picturability'* of that process .[184] There is supporting evidence for this hypothesis. For example, in his letter to me of 24-02-2004, Dr. Lawson said (unprompted): "I had a Faraday-type approach where most of my colleagues were Maxwell like." When Dr. Lawson was asked (during a telephone conversation of 22-03-2004) to elaborate on what he meant by having a "Faraday-type approach", he identified with Faraday's educational background in particular, saying that he was:

> "very much a sort of Faraday-style man - - of course Faraday had very little - - well he sort of worked up from a lowly position and educated himself on the way didn't he?
>
> **Ciara:** Yeah, as a book-binder.
>
> **Dr. Lawson:** I wasn't quite like that, but I certainly didn't have a degree in physics to start with. I did a degree in engineering... you have your feet on the ground a bit more if you're an engineer... "

When asked, in a subsequent questionnaire (04-10-2005), to what extent his ability to acquire physical or pictorial insight depended on his previous experiences: on his theoretical understanding, visual memories, fingertip/tacit knowledge, Dr. Lawson said:

> "most of my physics was self-taught, and is full of short-cuts and unorthodox analogy type connections. By going a strange route I often arrived before those that worked in a more formal and orthodox way (cf. Faraday and others?)... "

As mentioned in section 1.1, Faraday's motto was: *"Il faut savoir de manipuler,"* i.e. *"It is necessary to know how to handle/manipulate."*(cf. Tweney, 1985, p.196; Gooding, forthcoming in 2006, p. 5 of 24). The data thus suggests that, like Faraday, not only does Dr. Lawson seek a clear view of things, i.e. picturability or visualizability, he also seeks

[184]Gooding's studies on the work of Michael Faraday lead him to conclude that: "To Faraday, the intelligibility of a process often depended on achieving a 'clear view' of it. Thus, intelligibility meant picturability." (Gooding, 1992, p.143).

tactility or tangibility, i.e. getting a 'feel' for what he is dealing with. This is almost certainly on account of Dr. Lawson's training as a radio engineer: a *'backroom boy'* who has experience of (physically) tinkering with equipment [185] and had his "feet on the ground a bit more," as Dr. Lawson put it.

Bissell & Dillon tell us that: "simple... non-mathematical models... have led to engineers talking a language very different from that of conventional mathematics: a remarkably concrete language." (2000, p.10) In the case of Dr. Lawson, this is a language built upon physical and pictorial insights gained through analogical reasoning. He is a visualiser who uses sense-based concepts, not a producer of visualisable (math-based) representations as some questionnaire respondents quoted in section 3.5 were. For example, Phys_160, Phys_214 and Phys_198, who all raise concepts to a higher level of abstraction so that they visualise the mathematical structure not the physical entities to which they supposedly refer.

8.6 Conclusions

As we saw in chapter 7, Dr. Lawson had little formal physics education. He had an unconventional (2-year) wartime degree in the mechanical sciences with a strong engineering component. In particular he studied electrical engineering and radio, as a preparation for radiolocation (radar) research. He said he learned what he needed on the job surrounded by some of the best physicists and engineers in the country: first at TRE Malvern in the 1940s, then at Harwell in the 1950s, then at the Rutherford Appleton Laboratory in the 60s, 70s and 80s. Informal communication methods were encouraged at TRE in particular in order to facilitate quick problem solving (a matter of life and death during wartime). Because of this particular educational and research background Dr. Lawson often used unorthodox 'short-cuts' when problem solving. He found analogical reasoning to be a particularly useful conceptualisation and communication technique. Dr. Lawson employed: (i) physical and mathematical analogies with medium to high level systematicity, drawn from within the field of engineering (e.g. a biased pendulum provides an analogue of phase oscillations); (ii) pictorial and physical analogues with medium level systematicity, not confined to the field of engineering (e.g. water bag analogy to explain diffusion of a gas; cocktail mixing analogy to explain entropy). He employed these forms of analogy to good effect in his private conceptualisations to acquire physical and pictorial

[185] Dr. Lawson told me during a telephone conversation of 13-01-2005, "...I was working partly outside - - doing measurements on properties of the aerials - - like the angular distribution, polar diagrams or things of that sort."

insights for himself and when communicating with his peers in formal and informal setting to provide them with the same insights.

It would seem that for Dr. Lawson, acquiring pictorial insight means achieving a 'clear view' of something (as in Faraday's case), while acquiring 'physical insight' means achieving a 'clear view' plus a tacit 'feel' for something. This focus on tacit or kinaesthetic knowledge is almost certainly derived from Dr. Lawson's practically orientated research background. He said that the engineering component of his research background kept his feet firmly on the ground. As a result of his early experiences at TRE Malvern and Harwell he was acutely aware of the practical limitations when designing and building accelerators. In fact he became extremely well-renowned for his ability to critically assess concepts that people put forward and offer practical advice in the area of accelerator design.

The sociologist of science, Peter Galison (1997, p.781) contends that "... it is precisely the disunification of science that brings strength and stability." I agree that specialisation is vital for in-depth explorations in any domain. It allows sub-cultures of scientists to form, which have common languages of thought. Diverse specialisms bring strength and stability because they allow researchers in respective sub-disciplines to develop distinctive methodologies and terminologies: specialised and efficient ways of doing and presenting their research. My own studies also support Galison's (1997) view that sub-cultures of physicists and engineers communicate through developing 'contact languages'. I argue that **analogy** and **synthesis** are important components of these 'contact languages'. I support this claim through the case study of an engineer-physicist who employs analogy, firstly as a problem solving tool in his own work – to acquire insight for himself, and secondly to facilitate communications between sub-cultures of physicists involved in particle physics during the 60s, 70s and 80s. Analogy acts as a bridge between knowledge bases. The visual and kinaesthetic dimensions of analogy provide researchers in these different sub-fields with physical and pictorial insight. In this way Dr. Lawson acts as a translator, crossing boarders and bridging conceptual (or 'linguistic') divides between sub-cultures of physicists and engineers.

Dr. Lawson's unique research background was a vital component in his ability to act as a translator. The nature of his work meant that he was encouraged to explore four or five separate sub-fields of physics and engineering (applied optics, nuclear physics, plasma physics, high energy particle physics, and to a lesser extent astrophysics). This gave him a very broad viewpoint. These different perspectives enabled him to draw analogies between the underlying physics of these sub-fields, allowing for a cross-fertilisation of ideas. So, although he has always found it hard to get a mental picture of the physical processes involved in his research, his experiences in a range of sub-disciplines has allowed him to develop a richer, fuller picture over time. I believe that translators like Dr. Lawson play an important role in enabling sub-cultures of physicists and engineers to communicate and 'spark off new ideas'. From my Venn diagram in figure 5.3, the analogies used by Dr. Lawson fall within sets B and C. One could even sub-divide set C into sub-sets of experts. I suggest the skills of 'translators' like Dr. Lawson (e.g. their experience of using physical and pictorial analogies to offer insights to their peers) could be drawn upon by science communicators and science educationalists when 'translating' science to intermediates and novices too. They could use the skills of 'translator' physicists to generate 'good analogies' for use in set A as well as sets B and C. As I discuss in chapter 9, my research findings provide a good foundation for such a collaborative project.

9.0 Findings, Implications and Suggested Future Projects

In this final chapter I will recap on the four groups of research questions set out in chapter 1. As I have addressed each of these research questions in chapters 3-8, in this chapter I will focus on the most interesting findings and show that they fill several knowledge gaps in the literature. I believe that my findings have implications for several groups interested in conceptualisation and communication, including practicing physicists, science communicators, science educationalists, cognitive scientists and philosophers interested in abduction and model-based reasoning. I also suggest some in-depth follow-up studies which could be carried out by building upon my initial broad-ranging research findings.

9.1 Group 1 Research Questions: Visualisation.

As I discussed in chapter 1, detailed case-studies by researchers in the fields of history, philosophy and psychology of science (e.g. Gooding, Gorman, Gruber, Miller, Nersessian, Tweney etc.) have investigated scientists' personal difficulties in visualising aspects of their work, and personal techniques to over-come their visualisation difficulties. However, I found no broad-ranging quantitative accounts in the literature of the degree to which contemporary physicists find it difficult to get a mental picture of the physical processes involved in their research, nor of the types of techniques they report using to overcome difficulties they may have. Thus, I used the on-line questionnaire, follow-up e-mail exchanges and semi-structured interview with Prof. Berry to investigate the following research questions:

- *To what extent do a sample of physicists experience difficulties getting a mental picture of the physical processes involved in their research?*
- *What reasons do they give for having/not having these difficulties?*
- *Where physicists do have difficulty visualizing the physical processes involved in their research, how do they overcome this?*

9.1.1 Visualisation Difficulties

Although 3.6% of questionnaire respondents indicated that they have difficulty getting a mental picture of the physical processes involved in their research "7/all the time" (mostly on account of the highly abstract nature of their subject matter), a majority of the 225 physicists who responded to my on-line questionnaire were successful at overcoming their visualization difficulties through personal or communal strategies. Respondents mentioned using computer simulations, sketches, physical models that they can manipulate in their hands, mathematical analogies, physical analogies and pictorial analogies, or constructing mental pictures of mathematical structures rather than visualising the physical entities to which they supposedly refer. As I discussed in section 3.3, my findings on the techniques used by practicing physicists to overcome their visualisation difficulties have parallels with the findings of cognitive scientists such as Goel (1995) and Suwa, Gero, and Purcell (1999) on the visualisation techniques used by designers. Both groups use freehand sketches as a means of exploring newly formed conceptions. This process of externalising vague conceptions and playing with their spatial arrangements often offers clues on how to proceed. Similarly, my findings are in line with other studies in the field of cognitive psychology that suggest that peer collaboration is important to problem solving and that verbalising one's thoughts enhances one's problem solving abilities (e.g. Vygotsky, 1934, Chi, 1996).

9.1.2 Visual and Kinaesthetic Thinking in Science: Past and Present

I noted, in section 1.1, that Root-Bernstein (1985) posed an interesting question: "to what extent visual imagination is dependent or independent of the kinaesthetic skills of drawing or modelling." (p.63) I remarked that Gregory's (2001) work on the design of interactive science centre exhibits highlights the importance of **kinaesthetic skills** and **active touch exploration** in 'learning to see', and Gooding's (1992b, 1994, 2006) historical case study of Faraday's laboratory notebooks showed that fingertip knowledge gained through sheer persistence was instrumental in helping Faraday learn about the world. Several respondents who replied to the on-line questionnaire indicated that kinaesthetic skills of drawing and modeling were important facets of their visualization techniques. As discussed in section 3.8, I pursued this line of investigation in follow up e-mail correspondence with **Phys_2, Phys_27,** and **Phys_91**. These exchanges showed that the kinaesthetic skills of drawing and modelling - constructing physical models that one can see and touch and rotate in one's hands - were an important part of these physicists' visualization techniques. It is unclear to what extent these important skills are formally taught to physicists. Some physicists appear to develop these skills themselves prior to or in conjunction with their formal physics education. I suggest that all physics students should be formally taught to generate analogies, build mental and physical models and learn some basic drawing and drafting techniques (like those learned by some physics students and most engineering and architectural students) to strengthen their tacit and visual skills.

9.1.3 Visualisation Versus Visualizability: Past and Present

In section 1.1 I discussed visual thinking in science, drawing on key cases from the history of science. I noted that Einstein was a particularly visual thinker and that the visual images in his thought experiments were often drawn from the world of sense perceptions. I contrasted this with the approach of Heisenberg who sought “visualizability (visual images generated from scientific theories) and not visualization (visual images abstracted from phenomena we have witnessed in the world of perceptions.” (Miller, 2000, p. 310). My questionnaire data revealed that in areas where classical physics predominates, many contemporary physicists adopt Einstein’s characteristic mode of thought, based on visual images abstracted from phenomena that they have witnessed in the world of perceptions. They gain insights by employing mathematical, physical and pictorial analogies and performing thought experiments. For example, in section 3.7 I quote **Phys_54** as saying that: “In trying to do something really new, I go for that old method of Einstein, the Gedankenexperiment. I try to picture something visually in terms of things I believe correspond to measurements, and then think my way through it.” In contrast, in highly theoretical areas, at the forefront of research, many respondents said that they often abandon attempts to form mental pictures of the physical processes involved in their research and instead raise concepts to higher levels of abstraction and visualise the form of the equations representing the objects under investigation. For example, **Phys_214**, (a 24 year old, male PhD student) finds it quite difficult to get a mental picture of the physical processes involved in his research, because he deals with “quantum phenomena that do not always have classical counterparts.” To overcome these difficulties he says he must: “Raise concepts to a higher level of abstraction so that I visualise the form of the theory rather than the form of the objects involved.” Certain areas like high-energy physics have developed a very powerful graphical language that fuses mathematical intuition with visual imagery. Many physicists said that this helps them create the mental picture of the physical processes involved. Thus, my broad-ranging findings on the visualisation techniques used by contemporary physicists have parallels with accounts from the history of science, e.g. Holton (1978), Miller (1984, 2000).

9.2 Group 2 Research Questions: Computer Simulations

As discussed in sections 1.9 and 1.10 although Morgan and Morrison (1999), Hughes (1999), Winsberg (1999) et al discuss the use of computer simulations in science, there are few quantitative studies indicating the extent to which physicists, of different backgrounds, use computer simulations as visualisation tools. Thus, I devised several research questions which would go some way towards filling knowledge gaps in this area. I used the on-line questionnaire, follow-up e-mail exchanges with 13 questionnaire respondents, and interview with Prof. Berry to investigate the following novel research questions:

- *To what extent do these physicists employ computer simulations to help them visualise things?*
- *In what contexts do these physicists employ computer simulations?*
- *What reasons do these physicists provide for not using computer simulations in their research?*
- *Do these physicists believe that computer simulations have strengthened physicists' visualization capabilities (a) in their own research area? (b) in physics in general?*
- *What do these physicists believe are the possible disadvantages of employing computer simulations in research?*
- *Can computer simulations provide physicists with insights when conceptualising and communicating physics?*

9.2.1 The Contexts in which Respondents Find Computer Simulations Useful.

As I showed in section 4.1, there was a skew towards using computer simulations as visualization tools, with 48.2% of the sample selecting between **"5"** and **"7/all the time"** on the 7-point scale which ran from "never/1 – 2 – 3 – 4 – 5 – 6 – 7/all the time". In section 4.2 I presented examples offered by questionnaire respondents which ranged from visualizing complex geometries and interactions on nano-scales to those on giga-scales. For example, **Phys_201** said: "I use visualisation software to look at the atomic arrangements within crystal structures" while **Phys_21** said he simulates: "jets of gas from young stars - this helps enormously in understanding, particularly when coupled with animations of the results." Simulations are particularly useful when dealing with things that are difficult or impossible to physically manipulate. Thus, they are also used to design equipment and to explore the evolution of systems when subjected to a variety of boundary conditions. The broad range of contexts in which contemporary physicists find computer simulations useful was quite surprising. Examples of scientists' use of computer simulations to 'model reality' have been given by others. For example, in his paper, "Modelling Reality with Supercomputers" Catlow (1996) includes 28 snapshots showing the visual outputs generated by computer simulations, primarily in the field of atomic physics. However, my survey is unique in gathering quantitative data from practicing physicists on the extent to which they use computer simulations to help them visualise things, and qualitative data providing a range of contexts in which practicing physicists find computer simulations useful in their research.

9.2.2 Computer Simulations: Strengthening Physicists Visualisation Capabilities?

In section 1.10 I noted that the mathematician and educator Walter Whiteley (1992, web ref) has written on the importance of teaching students to see like a mathematician and underscores the value of computer software packages in this endeavour. Computer scientist and educational psychologist Barbara White (1993) and her **ThinkerTools** Research group also believe that computer simulations have their place in the classroom in helping students to conceptualise force and motion. According to artificial intelligence researchers Chandrasekran & Narayanan (1992, p.30): "Prior exposure [to diagrams and other kinds of images] can lead to perceptual fluency in recognition and classification." As a result of such findings, I was interested to survey practicing physicists to discover if they believed that computer simulations have strengthened physicists' visualisation capabilities. I believed that my questionnaire respondents would have a unique perspective as student, teacher and researcher, as many lecture or tutor at university level and all have all been students at some point. As I showed in section 4.1, a majority of questionnaire respondents felt that computer simulations "definitely have" helped strengthen physicists' visualization capabilities both in their **own research area** (51.6%) and **in physics in general** (52.5%). In their experience computer simulations are particularly useful for: (i) producing visual representations of complex geometries, which would be extremely difficult to mentally visualize; (ii) following the time evolution of complex systems; (iii) visualising the solutions of complex equations in graphical form.

The comments and examples presented in section 4.7 suggest that computer simulations do provide many physicists with useful insights even when their configurations may be unlikely. For example in a cosmological seeing, simulations are used to build simpler analytic models that are useful in making quantitative predictions about the implications of e.g. cosmic strings. When used in conjunction with formal mathematical analysis, computer simulations can provide physicists with insights which deepen their theoretical understanding. For example, Prof. Berry often made use of the generative power of computer simulations and used them to fine tune his geometrical intuition to a point where he had achieved conceptual fluency in navigating through abstract spaces constructed in his mind. However, many respondents were keen to emphasise that computer simulations offer little or no physical or theoretical *insight* if they are used as 'black boxes' where the user has little knowledge of the internal predictability of the model or the mathematical foundations upon which the model is built. I believe that my survey findings should be of interest to practicing physicists, and science educators who conduct work on the usefulness of computer simulations in 'teaching to see'.

Computer simulations are also particularly useful as a means of marketing physics: enlisting support from funding bodies, peers, and the general public by making good science look good. As we saw in chapter 4, Prof. Sir Michael Berry is acutely aware of the communicative power of his colourful pictures from the quantum world. He uses them to good effect when disseminating his work to audiences of experts, intermediates and novices. However he is also aware that the immediacy of his pictures may lead some non-experts to think that the pictures of abstract mathematical things are un-adulterated pictures of phenomena that exist in the physical world. Prof. Berry therefore uses artificial colours to prevent people from interpreting his pictures literally. Thus, my research has highlighted the fact that computer simulations are powerful discovery tools which must be used cautiously, informed by studies of this kind that draw on practitioners' own experiences of what works and what doesn't work.

9.2.3 The possible disadvantages of using computer simulations reveals interesting philosophical stances amongst respondents.

When pressed for the disadvantages of employing computer simulations in research 18 questionnaire respondents drew attention to the reality status of computer simulations. Respondents said that the models underlying the computer simulations should constantly be matched with experimental data. The experimental data in turn should be tailored to the computer models in order to test their internal predictive ability. However, on the whole, the majority of physicists seemed to be concerned with speed, efficiency, usability, empirical reliability and empirical adequacy. As I discussed in section 4.6.4, my survey data fit with the views expressed by Morgan and Morrison (1999) and Koponen (2006) – that most physicists are concerned with empirical reliability and predictive power of computer models and simulations rather than whether they accurately map onto reality.

As I discussed in section 4.5.4 many respondents remarked that it was in fact very difficult to distinguish between the use of computer simulations to solve problems and the use of computer simulations for the purpose of visualisation. For example, **Phys_160**, a

Reader in Theoretical Physics, said that, "it is probably impossible to distinguish meaningfully between (a) computations which produce the desired answers, conveniently presented in a visual format, and (b) the use of computer graphics to aid visualization. I think the two things are inextricably linked." My review of literature in the fields of history, philosophy, psychology or sociology of science suggests that there are no broad-ranging accounts of practicing physicists' views on the use of computer simulations as visualisation tools and/or tools of brute force calculation and the philosophical implications of this. Thus, I hope that philosophers of science will use my data as a starting point and explore these issues in more depth than was practicable within the scope and time of my project.

9.3 Group 3 Research Questions: Analogy

The second group of research questions I focused on related to physicists' use of **analogy** to conceptualise and communicate physics. Using the large-scale on-line survey and follow-up e-mail exchanges with a select sample of these respondents, I addressed the following research questions:

- *To what extent these physicists employ analogy in their research?*
- *What reasons do these physicists give for not employing analogy in their research?*
- *To what extent do these physicists generate* ***original*** *analogies in their research?*
- *To what extent do physicists use analogy when communicating with different audiences?*
- *What forms of analogy do they use in different contexts?*
- *What are the characteristics of a good analogy?*

9.3.1 To what extent these physicists employ analogy in their research?

The use of analogy in research was widespread among the physicists who responded to the on-line questionnaire. 52 respondents (23.1% of the sample) indicated that they use analogy "7/all the time" in their research. This is over three times as many as those that claimed to "never/1" use analogy in research. However, my research has shown that there are numerous and complex factors at play in physicists' use of analogy in scientific research.

A particularly interesting finding was that there was no unanimous definition of what constitutes analogy. Some physicists appeared to hold a narrow interpretation of analogy, which excluded formal mathematical analogies. This may be because the term "analogy" is usually associated with textbook physics or popular science books. (In fact the term metaphor was specifically avoided as it had poetic associations for many pilot study respondents). **Phys_185** said: "What I use is often stronger than analogies, in that the underlying mathematical description is the same or similar in the first approximation. For example, harmonic waves appear all over the place in very different physical situations." However, many other physicists referred to harmonic waves and LCR circuits as exemplary analogies. I found these results somewhat surprising, as e.g. cognitive scientists' research on analogy has not emphasised this ambiguity of meaning amongst scientific experts who employ analogy on a daily basis. Acknowledging the ambiguity in the way expert physicists interpret the term 'analogy' may go some way towards understanding why some physicists are enthusiastic about the use of analogy to conceptualise and communicate physics while others disapprove of it.

The reasons given by respondents for not using analogy in research fell into four main categories: (i) they didn't need to use analogy because their work was already easy to visualise, (ii) analogies were too difficult to formulate because their subject matter was highly abstract, (iii) analogies only seem appropriate for non-specialist audiences, (iv) analogies are overly simplistic and can be misleading. Although analogies can be particularly useful when dealing with concepts far beyond perceptual experience, such analogies can be misleading if taken too far. Therefore it is not surprising that some questionnaire respondents were overtly wary of analogy, saying it was overly simplistic and misleading to be of use to them. However, one should consider the possibility that these physicists may not have been thinking of analogy in the sense of abstract mathematical analogies that other respondents mentioned using in their research. Instead they may have been thinking of analogy in a simplistic sense, as it is often used in popular science books for example.

9.3.2 To what extent do these physicists generate original analogies in their research?

As I mentioned in section 0.1, the scientific enterprise requires physicists to retrospectively reconstruct events to convey a logical, deductive approach to problem solving and experimentation. As a result, analogies which may have been useful tools of conceptualisation in the early stages of theory building rarely appear in scientific papers. Thus, I was interested to survey physicists on the extent to which they generate original analogies in private conceptualisation and informal communication with peers. As discussed in section 5.4, **61.8%** of respondents selected in the **5-7** range regarding the degree to which they use analogy in research. However, regarding the degree to which they generate original analogies, almost the same percentage of respondents selected from the opposite end of the 7-point scale, with **60.8%** selecting in the **1-3** range (and 82.2% selected between 1 and 4). This suggests that a majority of respondents are aware that they mostly use an existing stockpile of tried and tested analogies rather than generating original ones. As mentioned in section 5.4, this finding fits with research by cognitive scientists such as Holyoak and Thagard (1995) and historians of science such as Nersessian (1995) who suggest that constructing analogies is cognitively more complex than using analogies.

A particularly novel finding related to the use of original analogies in research was the apparent censorship of creative language by some American Institute of Physics journals. This is related to the issue of reasoning by analogy because it is a consequence of journals requiring physicists to retrospectively present their work in a logical, deductive manner, editing out the creative insights and playful associations which led them to their discoveries. For example, as discussed in chapter 5, Prof. Sir Michael Berry coined the term *"diabolical point"* and used it to good effect in the titles of his public lectures to pique the listeners' curiosity and make the topic more memorable. The term *"diabolical point"* has been embraced by his peers, however the rules and conventions of *Physical Review Letters* prevent him from using the same creative language when communicating with his peers in this journal. It seems unfortunate that Prof. Berry's attempts to disseminate his ideas in an engaging and enlightening manner are thwarted by some physics journals with misguided notions of conceptual and linguistic purity. I believe that some physics journals should to be more open to the creative use of language (including analogies) in order to make for more engaging reading.

9.3.3 On the forms of analogy used in different contexts.

A remarkable 147 examples of analogies were provided by questionnaire respondents. From analysis of the on-line questionnaire data, the follow-up e-mail exchanges and interviews I can conclude that the complexities of analogies varies according to the context of use. Analogies on the simple end of the scale are common in (i) popularisations of science (e.g. one physicist compared quanta of energy in a quantum mechanical system to cents of euro in a monetary system in order to convey the quantization of energy to novices), and (ii) playful exploration of new ideas (e.g. Phys_134's mental image of a stadium helped him describe properties of D0-branes interactions). Analogies on the complex end of the scale are too sophisticated for physics novices to understand but are used by many physicists in their journal articles and conference talks. They are formal, mathematical analogies containing a high degree of isomorphism, i.e. there is a one-to-one

correspondence between the structures at a certain level of abstraction (e.g. "to regard the exact renormalization group as a continuum analogue of blocking on a lattice." Phys_170). In the middle of the scale are analogies that combine aspects of both simple and complex analogies. They are highly idealised, have a certain degree of isomorphism, and have pictorial and/or physical features. They have a heuristic function and are used by experts and intermediates to extend existing knowledge into a new domain. The historical analogy between the flow of **heat** and the flow of **electric charge** is one such analogy. It has physical and pictorial components: both systems can be visualized as incompressible fluids flowing within channels. Consequently the mechanisms which bring about the phenomena in the analogous systems can be compared and contrasted. It also has a certain degree of systematicity – as the analogy does not break down when taken beyond surface similarity.
My findings are in line with those of Dunbar (1999) and Cornelis (2000) in that analogies can be used to solve problems (design and fix experiments and formulate hypotheses) by transferring methodological approaches or comparing relational features between theories. Cornelis (2000) suggests a distinctive role for inter-disciplinary analogies as problem solvers and intra-disciplinary analogies as corollary generators in physics. I noted in chapter 1 that this distinction does not appear to be reflected in Dunbar's (1999) studies in the field of biology. I can conclude here that Cornelis' distinction is not clearly apparent in my data either. However, my research does provide supporting evidence for Nersessian's assertion that: " … analogies are not 'merely' guides to thinking, with logical inferencing actually solving the problem, but *analogies themselves do the inferential work and generate the problem solution.*" (1992a, p.20, italics in the original).

9.3.4 Factors which influence physicists' use of analogy when communicating with different audiences.

In section 6.2 I noted that the Bakthinian notion of 'addressivity' (Bakhtin, 1986, pp. 95-96) was a useful theoretical lens through which to view my data. I discovered that the majority of respondents attempt to take into account the "apperceptive background" of their audience in order to make their topic 'accessible'. The two most significant factors to influence respondents' use of analogy when communicating with different groups were the ***physics expertise of their target audience*** and *tone of the discussion.* Even though their target audience may have considerable expertise, when the context is informal and physicists are creatively playing with ideas in a relaxed setting, a much broader range of analogies are used. This ranges from analogies having well-established, underlying mathematical structure, to simple, playful analogies which break down if taken beyond surface similarity. When the context is more formal, physicists tend to avoid the playful analogies, employing only analogies with a well-established underlying mathematical structure; what **Phys_127** termed, "rock solid analogies." Avoidance of analogy in formal settings is more common amongst **young physicists** who wish to be taken seriously by their peers and superiors, and consequently adopt a formal, dignified tone. Those who have already established themselves as noteworthy physicists can afford to be more flippant in formal settings because they have nothing to prove. However, with a high-ranking position comes a responsibility not to mislead their audience by using overly simplistic analogies. Thus, respondents will either use <u>fewer analogies</u> or <u>more complex analogies</u> as their audience's physics expertise increases, because they do not wish to present an over-simplified view to those with considerable expertise. As a consequence, it is those who are least able to evaluate the merits of an analogy that are most likely to have analogy used on them. However, I argue in section 6.7 the group most at risk of misunderstanding analogies, adopting a naïve interpretation of analogies or failing to see the limits of analogies are secondary and **tertiary level students**. These intermediates are encouraged to use simplified models and analogies on a regular basis in their formal education in order to solve specified problems. Once assimilated, the models and analogies become part of their conceptual toolkit. As a result of their practicality they are taken by many to be realistic, 'for all intents and purposes', and may even cease to be regarded as 'analogies'. We know from Spiro et al's (1989) research that even when the **disanalogies** are made explicit to medical students, many still hold erroneous assumptions, misled by connotations of non-technical descriptive language.

9.3.5 Mapping from a commonplace source to a specialised target

A finding which I believe will be of particular interest to science educationalists, was on the issue of **'mapping'.** The examples of original analogies offered by **Phys_63** and **Phys_193** in section 5.4.1 are similar to what Dunbar (2001) would call *long-distance* analogies, where the scientist maps from a commonplace *source domain* (a snickers bar or a cheese sandwich) to a more specialised target domain (a bar-shaped galaxy or a parallel plate resonator). This kind of mapping allows one to remember a key point in a very simple way. It acts a scaffolding or framework with which to build one's theory or explain one's concept. I believe that original analogies which feature physically **possible** but **implausible** situations may be less likely to mislead novices. For example, firing positrons from a particle accelerator is often likened to firing little blue balls from a gun. To the eyes of a novice, there is significant literal similarity between the source domain (little blue balls being fired from a gun) and target domain (positrons being fired from an accelerator). Without proper guidance, some novices are misled into thinking that positrons 'really are' little blue balls. Instead of comparing positrons to inanimate objects like little blue balls, Professor Paul Coleman's playful explanation of positron surface interactions compares positrons to chickens. In follow-up e-mails, Prof. Coleman explained that he "doodled" the Dazed Chicken Model during a "far from interesting" conference talk. He said:

> "My intent was to have some fun and to lighten what was a very boring time. But the sketch has since amused many of my colleagues in positron physics, and I am now using it in a short presentation to potential students and their parents on UCAS admissions days in the Department."

The entertaining verbal analogy and accompanying sketch are easily visualised and extremely accessible for physics novices. Professor Coleman's analogy also contains little **literal similarity** (thus novices are not misled into thinking that positrons are literally similar to chickens, or that an atomic lattice is literally similar to a forest of evenly spaced trees) but contains **considerable systematicity**: There is a one-to-one correspondence between the elements of the source and target domains for a hierarchy of relations. This ranges from non-literal relations between the source and target on a physical or pictorial level (e.g. chickens being like positrons), down to mathematical relations that exist on a deeper structural level (e.g. the shape of the ravine could be thought of as a mathematical function relating to a potential well in which positrons can be trapped near a solid surface). The physical picture attached to the physically possible but implausible source can thus be used as a bridge to understand the physics of positron surface interactions.

From my analysis of the data presented in chapters 5 & 6 I can suggest that good analogies tend to have the following features: Good analogies that appear in set C of my venn diagram in section 5.5 are useful heuristics (i.e. rules of thumb) in problem solving and generative (i.e. suggesting new avenues to pursue through more rigorous analytical means). Good analogies that appear in the sets C and B of my venn diagram hold for a hierarchy of relations (from the mathematical equations governing the system to the physical and pictorial expression of system features). Good analogies that appear in sets B and A, are easy to express (pictorially, verbally, symbolically) and are useful in different contexts (formal & informal settings; with experts, intermediates & novices). Analogies which span all three sets, A, B and C are often those whose origins can be traced back to eminent physicists. The same analogous idea can be used in different ways in different contexts. For example, as discussed in section 5.6.1, an analogous visualisation of loops and weaves is used by Rovelli (2003) to help **Physics World** readers conceptualise these highly abstract entities. However, at a conference of experts, Rovelli (2000) uses a humorous sketch of loops being woven into a jumper to highlight the fact that the analogous visualisation should not be taken too literally. The appropriateness of an analogy is highly dependent on the context of use: the formality of the occasion, the expertise of the audience and the main goals of the individual employing the analogy.

I believe that these findings will be of interest to practicing physicists interested in the forms of analogies used by their peers to conceptualise and communicate physics in different contexts and may also be of practical use to science educators. For example, my identification of the features of good analogies could be used in future research projects to devise a searchable databank of good analogies (see next section). This would will involve collaboration between practicing physicists with a flair for communicating with different audiences; science educators who have experience of students' differing learning styles; and researchers like myself, who approach the area through the lenses of history, philosophy and psychology of science. Such a resource could then be used to train science students to use conceptualisation techniques similar to those used by practicing physicists – in particular, the use of playful analogies, structured so that they hold for a hierarchy of relations but are generative and expressed physically, pictorially and mathematically.

9.3.6 Possible Future Project: 50 Of The Best Models and Analogy for Use in Science Education

As mentioned at the outset, this project could be classified as 'action research'. It is my hope that my research will be of use to practicing physicists and science educators interested in issues surrounding conceptualisation and communication in physics. I will make my thesis available to download on-line, via the website of the Science Studies Centre, Department of Psychology, University of Bath and write a brief summary of the main findings of my research. I will put this summary on my website and broadcast it in the same way I broadcast my on-line questionnaire: via popular science magazines such as Physics World (with whom I have worked in the past) and by e-mailing the 3,200 physicists based at universities in the UK whose e-mail addresses are stored in a mailing list I constructed in 2003. I will also create a new mailing list containing physicists specifically involved with the science education branch of the Institute of Physics.

I will encourage debate on my main findings and ask physicists to e-mail me with their favourite models and analogies for use with students in secondary and tertiary levels of education. Over the following year, I will compile these models and analogies and devise a methodology by which to evaluate their effectiveness. This methodology will involve collaboration between practicing physicists, science educators and science students. Funding permitting, I will carry out this research and produce a searchable on-line database of 50 of the best models and analogies for use in science education. This will be searchable by keywords such as "electrostatics", "magnetism", "nuclear", etc. It is my hope that this resource will be valuable to science educators around the world. To avoid copyright infringement, I will give credit to the physicists who provided me with their descriptions of these models and analogies, and set up a research fund to which people may voluntarily contribute if they find the resource useful.

9.4 Group 4 Research Questions: Case Study of a Physicist-Engineer

I used the findings of the large-scale survey to guide my case-study investigations. I addressed the following research questions:

- *To what extent did the case study respondent (Dr. Lawson) experience difficulties getting a mental picture of the physical processes in his research?*
- *What reasons were given by Dr. Lawson for having/not having difficulty?*
- *How did educational, professional, cultural, historical, etc. aspects impact on Dr. Lawson's approach to problem solving?*
- *To what extent did Dr. Lawson use analogy to acquire and promote insight?*
- *How does* ***physical*** *insight differ from* ***pictorial*** *insight in Dr. Lawson's view?*
- *To what extent did Dr. Lawson use analogy to bridge sub-disciplinary boundaries?*
- *What types of analogies did Dr. Lawson employ in this context? I.e. were they within domain or between mappings, physical, pictorial, mathematical etc.*

9.4.1 The Use of Analogy To Provide Physical and Pictorial Insights

My own studies support Galison's (1997) view that sub-cultures of physicists and engineers communicate through developing 'contact languages'. I argue that *analogy* and *synthesis* are important components of these 'contact languages'. I support this claim with the findings of my survey of 225 physicists from across the physics community and particularly with the findings of my case study of Dr. J.D. Lawson, a retired engineer-physicist who employed analogy: (i) as a problem solving tool in his own work – to acquire insight for himself; and (ii) to facilitate communications between sub-cultures of physicists involved in the physics of charged particle beams during the 50s, 60s, 70s and 80s. I argue that analogy acts as a bridge between knowledge bases. The **visual** and **kinaesthetic** dimensions of analogy provide researchers in these different sub-fields with physical and pictorial insight. This can be: (a) *pictorial insight*, i.e. creating mental pictures of physical phenomena or of mathematical structures; (b) *physical insight*, i.e. helping one to get a 'feel' for how a system behaves by giving it a tacit, kinaesthetic component. The research backgrounds of physicists who employ analogy in this way can be an important factor. Certain branches of physics appear to be more open to analogical reasoning than others. For example, J.D. Lawson's unique research background was a vital component in his ability to act as a translator. His penchant for analogical reasoning was almost certainly a result of his working environment at Malvern, Harwell and the Rutherford Appleton Laboratory. The nature of his work meant that he had the opportunity to explore five separate sub-fields of physics, giving him a particularly broad viewpoint. These different perspectives enabled him to draw analogies between these sub-fields, allowing for a cross-fertilisation of ideas and techniques. He was often invited to give the opening or summing up talk at conferences in the hope that his ability to bring together the disparate sub-branches would spark off new approaches.

In conclusion, my research clearly shows that analogical reasoning is an important model-based reasoning technique used by many physicists to (i) bridge conceptual divides between, experts and novices, scientists from different disciplines, and even specialists within the physics community; (ii) 'promote' their research, i.e. to make their research accessible and memorable to peers, funding bodies, prospective students, and the general public, thereby enlisting support.

9.5 Inadequate Operationalization or Genuine Sub-Cultural Differences?

One of the first interesting elements to emerge from the on-line questionnaire data was the fact that respondents' had different interpretations of terms such as *analogy, visualization,* and *computer simulation.* As discussed in chapter 2, although this usually indicates inadequate operationalization[186] in the design of a questionnaire, it was in fact a conscious decision to give no definitions of these terms. I reasoned that allowing physicists to interpret the terms for themselves, to discover what e.g. *computer simulation* means to them, might highlight trends in interpretation across the physics community. At the very least it would help to develop a nuanced classification of the terms. This method proved quite successful. The initial discoveries from the on-line questionnaire could be taken on board and pursued further in the other strands of the project (e.g. the follow-up e-mail

[186] "Operationalization refers to the rules we use to link the language of theory (concepts) to the language of research (indicators)." Rose, D. & Sullivan, O. (1996) **"Introducing Data Analysis for Social Scientists"** 2nd edition. Open University Press, p.13

exchanges, in-depth interviews and the case study) and the distinctions and subtleties teased out. Thus, this issue highlighted the strength of the overall design of the project. By moving between large-scale survey data and small-scale case study data, a more detailed and colourful map of the territories under investigation could be drawn.

Differences of interpretation of terms like 'analogy' and 'computer simulation' revealed some physicists' hidden preferences for one way of reasoning and dislike for other, "simplistic", ways of reasoning. These differences of interpretation also revealed 'sub-cultural' differences: while there are no definite boundaries between experimental physics, theoretical physics, computational physics, and mathematical physics, with many physicists frequently moving between these domains, some physicists saw significant differences between so-called 'experimentalists' and 'theorists'. For example, when asked: *"Q4. In your research, do you ever use computer simulations to help you visualise things?"* **Phys_19**, a Professor of Theoretical Physics, selected *"7/All the time"* from the 7-point scale which ranged from *"1/never"* to *"7/All the time"* and when asked in **Q4b** to supply an example, he replied animatedly:

> "I detest the word 'simulation': this is an experimentalist's derogatory description of modelling, algebra, analysis, numerical analysis, computational physics, computer programming, checking, testing etc etc. I effect theoretical and computational physics calculations as a large part of my research job (Personal Chair)" [187]

In the Additional Comments section of the questionnaire he further stressed the apparent divide between experimentalists and theorists saying that:

> "The average Experimental Physicist, in my experience knows very little mathematics. On the other hand, it is sufficient that I understand the import and the limitations of experiments." (Phys_19)

Meanwhile, a physicist near the other side of the divide, **Phys_9,** a lecturer in Physics & Astronomy, explained that the visualization difficulties he occasionally experiences are mainly due to the fact that:

> "Theoreticians generally don't present their work in a suitably 'visual' sense. It can be hard to visualise equations into their physical meaning without adequate diagrams etc." (Phys_9) [188]

The comments of **Phys_165,**[189] an advanced research fellow, involved in particle physics, touched on several the sub-disciplinary or sub-cultural differences in the field of physics.

[187] **Phys_19**: A 60 year old, male, Professor of Theoretical Physics, whose research interests include, "Atomic,molecular and optical and condensed-matter physics,occasionally nuclear. Notably:hevy-particle collision theory,Wannier above & below theshold phenomena and ferromagnetism,including fractals."
[188] **Phys_9,** a 32 year old, male, Contract Lecturer in Physics and Astronomy, whose research interests include: Astrophysics; Image Processing; Imaging Instrumentation; and Data Mining,

He said it was important to recognise that there was a distinction between pure science and applied science; between experimentalists and theorists; between mathematical analogies and physical analogies; between internal, mental visualizations and external visualizations, generated by computers or when sketching by hand; and lastly between visualization and simulation. Consequently, the questions were likely to be interpreted differently depending on the physicists' research background, training, research interests etc. He wrote:

> "It is hard to formulate the same questions when dealing with applied and pure science, with theoretical and experimental studies. Maybe one should have different sets of questions for these target groups. For instance I do many 'Gedankenexperimente' and also 'computer experiments' (i.e. simulation) but experimentalists mean quite different things when they use this word. So I found some questions hard to answer. Analogy and visualisation are also two completely different things. Working in theory I always see analogy because the mathematics is the same even when physics might look differently. Then there is visualisation which can either be mental (I tend to think very graphically, others more algebraically etc), computer visualisation or just sketching pictures. Last the use of computers in 'visualisation' and 'simulation' should probably be seen as quite separate hats." (Phys_165)

The discovery of these subtle sub-cultural perspectives is very interesting and worthy of further investigation.

9.5.1 Possible Future Project: Exploring the preferred modes of communication of sub-cultures of physicists.

To further explore the sub-cultural differences which emerged in my PhD work, one could select a sample of 100 physicists, representing different 'sub-cultures' of physics. The database of 225 respondents of the on-line questionnaire could prove useful for selecting these physicists. The group would be given a selection of scientific papers and popular science articles spanning a 100-year period. These papers would use graphical representations, mathematical analogies, physical analogies, pictorial analogies, and creative language to varying degrees. The group would be asked to comment, for example, on the papers' intelligibility and rigour, as well as the stylistic features they particularly liked or disliked. The comments would be both qualitative and quantitative. For example, they could quantitatively select from a 5-point scale, ranging from "extremely unintelligible" to "extremely intelligible" and then explain their selection qualitatively by giving a textual reply via e-mail, or a verbal reply via telephone or in person. There would be a policy of anonymity or confidentiality with regard to specific responses, but

[189] **Phys_165**, a 36 year old, male, advanced research fellow, whose research interests include, Particle Physics, Computational Physics, Hadron Physics, Lattice Gauge Theories, QCD.

permission would be sought to acknowledge all respondents in aggregate, by a listing of their names and institutions. These physicists would know that their peer reviews would not be passed onto the editor of a specific journal with characteristic conventions and norms. Thus, they could give a more frank account of what they themselves think about the papers. This would give a better understanding of the characteristics that are valued across sub-cultures of physics (e.g. proof through rigorous, abstract mathematical content; exemplification or comparison through use of pictorial or physical expressions). One could explore whether papers which cut across disciplinary boundaries rely on pictorial and physical modes of expression to a greater extent than papers which deal with subject matter which is confined to a single branch of research. This study would provide a better understanding of the modes of communication preferred by sub-cultures of physicists.

9.5.2 Possible Future Project: Observation of Photonics Crystal Fibre Team

Much of a physicist's knowledge is tacit and therefore difficult to elicit through questionnaires or interviews (See Collins, 1982). Utilising the approach of psychologists such as Dunbar (1995) and Klahr (2002) and of sociologists and anthropologists such as Latour (1987), Traweek (1988) and Forsythe (1993), one could observe physicists in action. This would involve sitting in on lab meetings, and recording discussions between physicists to obtain observational evidence of the use of analogies and visualization in intra-group communication. In their studies of changes in the representation of visual scientific data, Trickett, Fu, Schunn & Trafton (2000, p.959) focused on pairs of scientists rather than an individual scientists because in their view:

> "dyads produce speech naturally as part of their data analysis activities. By contrast, focusing on an individual scientist to give think-aloud protocol may change the very representation that we seek to study. For example, the individual scientist may change her focus to aspects of the data that are more easily verbalized, or she may change her representations from visio-spatial representations to more verbal representations."

Key members of the Photonics Crystal Fibre (PCF) team, an innovative group working within the University of Bath's Physics Department, could be taken as a case study. For example, one could focus in particular on Prof. Jonathan Knight and Prof. Philip Russell. The PCF team work in both an academic and an industrial environment, which would provide a useful contrast and comparison to the case study.[190]

[190] Incidentally, Phillip Russell and J.D. Lawson have both, independently, been awarded the Thomas Young Medal from the Physical Society for the work they have done in optics, Russell in 2004 and Lawson in 1985.

9.6 Implications of Main Findings And Concluding Comments.

As I have mentioned on several occasions in this chapter, the insights gained from my research should be of interest to practicing physicists interested in the way their peers conceptualise and communicate physics, cognitive scientists and philosophers of science interested in model-based reasoning in science, and educators wishing to promote similar model-based reasoning skills among physics students (particularly at secondary and tertiary levels of education). In particular, I hope that my findings regarding the features of 'good' analogies may be useful to science educators when devising or evaluating the likely efficacy of an analogy.

As Feist and Gorman's (1998) Structural Equation Model (shown in fig. 1.1) indicates, innumerable factors influence scientific thinking. One may look at it from a number of perspectives: developmental psychology, cognitive psychology, social psychology, etc. My interdisciplinary research project was not intended to make law-like generalisations about scientific thinking (as psychologists often do), nor to give strict definitions of terms like analogy, visualisation or computer simulation (as philosophers often do). My main aims were:

(i) to identify knowledge gaps by surveying literature in diverse but (to my mind) inter-related fields like history & philosophy of science, cognitive science, sociology of science, science education, literary theory, design studies, etc.

(ii) to explore these novel questions using innovative data gathering methods which combine some of the most useful methodological approaches from these diverse but inter-related fields, given the time and funding available;

(iii) to produce interesting findings which go some way towards filling these knowledge gaps and which spark off further studies by researchers in a variety of related fields.

The positive feedback I have received from historians of science, philosophers of science, cognitive scientists and science educationalists, after presenting my data at interdisciplinary conferences in the UK and abroad, suggests to me that I have achieved these main aims. I am confident that this broad-ranging, interdisciplinary study will catalyse further, more in-depth studies in future, and have a useful impact in fields associated with model-based reasoning in scientific research and science education.

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Topic	Type	Author(s)	Key issues
Visual Imagery and Representation	Philosophical arguments	Tye, 1984; Block, 1981; Dennett, 1981; Rollins, 1989; Motzkin, 2002;	"The issues for representation are then two: first, the primacy of perception in forming representations, and second the question of the existence of mental images. One can have a perceptual theory of representation without having an imagistic one, one can have a non-perceptual theory of representation, but it is not clear that one can have an imagistic theory of representation without having a perceptual one." (Motzkin, 2002. p.206)
	Psychological data	Shepherd and Metzler, 1971; Metzler and Shepard, 1974; Paivio, 1977; Kosslyn, 1980, 1981, 1983; Kosslyn and Pomerantz, 1981; Pylyshyn, 1981; Finke and Pinker, 1982; Shepard, 1982; Shepard and Cooper, 1982; Kolers & Brown, 1984; Finke, Pinker & Farah, 1989;	**Reference:** How does an image refer to the imaged object? **Cognitive Architecture:** Do there exist cognitive structures and processes dedicated to processing visual information? Or are such processing handled by general purpose structures and procedures? "This question seems to be the primary focus of the picture/word processing literature (Kroll and Potter, 1984; Paivio, 1977; Potter, So, Eckart, and Feldman, 1984; Snodgrass, 1984; Snodgrass and Vanderwart, 1980; Vanderwart, 1984). I think there are some conceptual problems with this literature and refer the reader to Kolers and Brown (1984) for an interesting critique." (Goel, 1995, p.183) **Format:** Does the processing of images involve: (1) "computations defined over geometric data structures specified in terms of points, vectors, surfaces, or volumes, which can support geometric operations, such as rotation, translation, zooming, perspective transformations, and the like, or (2) relational structural descriptions of some kind (e.g. under [ball, table]), which support logical inferences." (Goel, 1995, p.184)
	Neuropsychological data	Farah, 1989; Kosslyn, Alpert, Thompson, Maljkovic, Weise, et al., 1993 Kosslyn, Thompson, & Alpert, 1997;	**Cognitive Architecture:** Does imagery utilize the same cognitive structures and processes, possibly even the same neural pathways, as the visual-perception system? (Finke and Shepherd, 1986; Kosslyn et al., 1993)
	Computational Models	Schwartz and Kosslyn, 1982; Funt, 1983; Glasgow and Papadias, 1992;	"Computational imagery involves tools and techniques for visual-spatial reasoning, where images are generated or recalled from long-term memory and then manipulated, transformed, scanned associated with similar forms (constructing spatial analogies), pattern matched, increased or reduced in size, distorted, etc. A primary goal of our approach to computational imagery is to facilitate the retrieval of visual and spatial information that was not explicitly stored in long-term memory. The images generated to retrieve this information may correspond to representations of real physical scenes or they may be abstract concepts that are manipulated in ways similar to visual forms." (Glasgow & Papadias 1992, p.356)

Table A1.1: Brief Overview if literature related to Visual Imagery and Representation

Topic	Key Issue	Specific Findings	Author(s)
Representation	Diagrammatic Reasoning	All necessary reasoning is diagrammatic	Peirce, 1906, p. 314
	Internal : External	Do scientists "tend to think of their data in formal, discipline-specific terms, or do they rely on more informal and simple perceptual terms?"	Trickett, Fu,, Schunn & Trafton, 2000, p.959
	Formal : Informal	"The scientists initially represented expected findings in formal, scientific terms, whereas they represented anomalies in informal terms. Over time, these representations shifted from informal to formal. We propose that this shift in representation is the result of an increased understanding of the individual phenomena, rather than of greater understanding of the data at a global level."	
	Perceptual fluency	"Prior exposure can lead to perceptual fluency in recognition and classification."	Chandrasekran & Narayanan, 1992;
	sketching	"Schon and Wiggins (1992) argue that sketching plays an essential role in the conceptual design process by evoking unexpected discoveries and through a process of reinterpretation. Designers do not necessarily interpret design sketches with the same meanings, but reinterpret them with new meanings. Goldschmidt (1991) calls this reinterpretation process a 'seeing-as' activity, while Goel (1995) calls it 'lateral transformation'." (Kavakli, Suwa, Gero and Purcell, 1999, web ref.)	Kavakli, Suwa, Gero and Purcell, 1999, web ref,
		"drawing free hand sketches during conceptual design plays a crucial role in the birth of creative ideas. Design sketches serve as a medium through which a designer makes visual/spatial reasoning; a designer externalises newly formed but still vague ideas in the form of less rigid and ambiguous depictions on paper. By inspecting those externalised ideas, the designer finds useful clues to refine them, which motivates him or her to draw again. In Schon's terminology, the designer is having a "reflective conversation with his or her idea" (1983)." Suwa, Gero, and Purcell, 1999;	Robbins, 1994; Schon, 1983; Banerji and Elmitt, 1994; Goel, 1995 Suwa, Gero and Purcell, 1999
	Conceptualisation : Communication	The external representations that are best for discovery are not necessarily best for communication of the discovery to others.	Trickett, Schunn & Trafton, 2000, p.959
Explanations	in science & science education	Provide a typology of explanations, focusing on the notion of "appropriateness";	Gilbert & Boulter, 1998a, 1988b;
		Speech Genres: Addressivity - taking into account the apperceptive background of one's audience, i.e. the scope of the addressee's specialised knowledge.	Fleck, 1935; Bakhtin, 1986; Harré, 1990;
		Building on Martin's (1972) system of classification, Gilbert and Boulter (1988a) set out 5 meanings for the term "an explanation" in science and science education: (1) Intentional; (2) Descriptive: (3) Interpretive; (4) Causative; (5) Predictive.	Martin, 1972; Gilbert & Boulter, 1998a, 1988b;

Table A1.2: Brief Overview of Literature relating to Representations and Explanations

Topic	Key Issue	Specific Findings	Author(s)
Model-based reasoning researchers' studies of contemporary experts' and novices' use of **metaphor** and **analogy** have shown that there are	upsides to employing metaphor and analogy	Creating and using analogies facilitates insight and scientific discovery;	Clement, 1982; Carbonell, 1983, 1986; Nersessian, 1988, 1992a, 1992b, 2002, 2003 Gentner & Jeziorski, 1989; Vosniadou and Ortony, 1989; Dunbar, 1995; Bailer-Jones, 1999, 2002; Cornelis, 1999; Dunbar & Blanchette, 2001;
		The most successful labs make use of local, domain-specific analogies and heuristics	Dunbar ,1995, 1997, 1999;
		"A single metaphor is always imperfect, but a set of metaphors all almost converging on the same target do illuminate and define it (Bergson, H., 1912, p. 20-21)." (Gruber, 1995, p.402)	Gruber, 1995
	downsides to employing metaphor and analogy	People do not have the option to ignore the non-literal meanings of sentences. Instead, people seem to process both the non-literal and the literal meanings of sentences in the same way, and at the same time.	Glucksberg, Gileda & Bookin, 1982
		It is better to provide people with descriptions of the mechanisms involved in a system rather than analogies because people tend to make wrong mappings more often than right mappings.	Halasz & Moran, 1982;
		Simple analogies that help novices gain a preliminary grasp of difficult, complex concepts may later become serious *impediments* to fuller and more correct understanding.	Spiro, Feltovich, Coulson, & Anderson, 1989;
		Baroque tower on a gothic base	Blanco and Niaz, 1998
		"The creation of a profound analogy is unlikely to depend in preexisting rules that establish mappings between the source and target domains. The innovation indeed depends on the invention of such rules." (Johnson-Laird, 1989, p.327)	Johnson-Laird, 1989

Table A1.3: Brief Overview of Literature related to the use of metaphor and analogy in science

Research Field	Key Issue	Specific Findings	Author(s)
Logico-Philosophical Perspective on Analogy	Difference between strong and weak analogies	"The acceptance of a solution following from a weak analogy always hinges on considerations that are independent from the analogy…[While] a solution obtained on the basis of a strong analogy may be justified by simply referring to the corresponding fact in the source domain." (Meheus, 2000, p.26) "…the combination of ampliative and deductive steps may cause the reasoning process to be *dynamical.*" (Meheus, 2000, p. 27)	Meheus, 2000;
Historical case studies are not intended to support general, cognitive theories about the processes at work. Instead they have shown:	inventors search in dual space	Wright brothers made use of dual space	Bradshaw, 1992
		Bell made use of mental models and heuristics in the invention of the telephone	Gorman, 1995
	importance of **tacit knowledge**	Faraday used a large repertoire of hands-on procedures, which influenced his mental models	Gooding, 1985, 1990
	Perceptionally based → propositionally based	In physics, imagery and metaphor have changed from being perceptionally based to being propositionally based	A.I. Miller, 1989
	Upsides and downsides of **metaphor & analogy**	Use of metaphor and analogy is critical to creation of scientific knowledge;	Dreistadt, 1968; Nersessian, 1988, 1992a, 1992b, 2002, 2003 DeMay, 1989;
		Conceptual schemes can greatly inhibit the creation of new knowledge.	DeMay, 1989;
Cognitive Neuroscientists'	studies of analogy indicate that certain areas of the brain are hardwired for analogical reasoning	The dorsolateral prefrontal cortex (DLPFC) may be specialized for binding arguments to complex mental representations.	Grafman, 1995; Fuster, 1995; Robin & Holyoak, 1995
		Analogical mapping may be an emergent special case of this general property of the DLPFC	Wharton, Grafman, Flitman, Hanses, Bruner, Marks, & Honda, 2000;
		The left angular gyrus may be hardwired for analogical reasoning	
		Analogical mapping is mediated by the left prefrontal and inferior parietal cortices	

Table A1.4: Brief Overview of Literature relating to analogy

A2.1 The following 9 pages contain a print out of my on-line questionnaire: http://www.bath.ac.uk/psychology/research/physics.cfm

Conceptualisation and communication in contemporary physics

Introduction:

My name is Ciara Muldoon. I'm a PhD student at the Science Studies Centre, University of Bath, UK. I have a BSc in Experimental Physics and an MSc in Science Communication. I'm currently researching conceptualisation and communication in contemporary physics. Exploring this topic is extremely important, because as physics becomes increasingly specialised, the free flow of ideas, both across and within disciplines, needs to be actively maintained. Likewise, the bridge between researchers and the public must remain intact for physics to be appreciated.

UPDATE: 23 Jan 2004 Many thanks to everyone who responded to this questionnaire between February
and June 2003. Some very interesting material has resulted from your comments and suggestions.

Preliminary analysis has revealed some interesting trends, but no conclusions can be drawn until further, in-depth case-studies are performed. These are
currently underway and I hope to be able to provide you with some detailed
feedback in Spring/Summer 2006.

Best Wishes,
Ciara Muldoon

Below is a questionnaire addressing five topics:

1. **Research Background;**
2. **Visualisation;**
3. **Analogy;**
4. **Computer Simulations;**
5. **Physics Communication.**

By taking the time (about 15 mins) to complete this questionnaire, you will be providing valuable insight into scientific reasoning and communication. Your contribution will, of course, be anonymised. The findings of my research should benefit the entire physics community as I aim to publish them in *Physics World, New Scientist* or similar publications.

If you would like confirmation of my aims, you may contact my supervisor Prof. David Gooding

E-mail address: d.c.gooding@bath.ac.uk

Home page: **http://staff.bath.ac.uk/hssdcg**

NB: you can use the **Tab** key to move from one field to the next. **Shift + Tab** will take you back to the previous field.

If you are on a modem connection, you can download a **Word version of the form**. *(If you do not have Word you may require a Word document reader to open this file:* ***Open Office*** *-* ***download****, or* ***Word viewer*** *are available)*

Q. Would you like to receive feedback on the findings of this study? Select one

1. Research Background.

Q1. **What 3rd level qualifications do you hold?**

Subject area (e.g. BSc in Experimental Physics, MSc in Opto-electronics, PhD in Astrophysics):

Diploma: Select one

BSc: Select one

BEng: Select one

MSc: Select one

PhD: Select one

Post Doc: Select one

Other (Please state): Select one

Q1a. With which of the following groups would you associate yourself?

Applied Optics: Select one

Chemical Physics: Select one

Computational Physics: Select one

Surface Science and Technology: Select one

Nuclear Physics: Select one

Plasma Physics: Select one

Condensed Matter and Materials Physics: Select one

High Energy Particle Physics: Select one

Mathematical and Theoretical Physics: Select one

Spectroscopy: Select one

Quantum Electronics and Photonics: Select one

Astrophysics: Select one

Other - please state here:

Q1b. **What is your present job title, occupation or course of study?**

Q1c. **Gender:** Select one

Q1d. **Age:**

Q1e. **What are your present research interests?** (Brief explanation; please include keywords, e.g. plasma, acoustics, opto-electronics, etc.)

---

2. Visualisation.

Q2. **Do you ever find it difficult to get a mental picture of the various kinds of physical processes involved in your research?**

The drop-down box contains a scale ranging from "never" to "all the time". Please select the number that best suits your response. Select one

Q2b. **Why do you think this is?**

Q2c. **Where you *do* have difficulty, how do you overcome this?**

Q2d. **How often do you visualise experiments which are:**

(i) then physically performed Select one

(ii) too expensive or technically difficult to physically perform Select one

(iii) physically performable, but doing so would offer no further insight Select one

(iv) impossible to physically perform Select one

---

3. Analogy.

Some physicists use analogy in their research.

- e.g. using a billiard ball model when considering the movement of charge through a solid;
- e.g. comparing ultrasonic transmission down a rod, to an electrical transmission line;
- e.g. comparing the vibrations of a 'cosmic string' to the vibrations of a guitar string;
- e.g. Schrödinger's equation is derived by using Hamilton's mathematically unified treatment of geometrical optics and analytical mechanics;
- e.g. Sheldon Glashow has remarked that he "was led to the group SU(2) x U(1) by analogy with the approximate isospin hypercharge group which characterises strong interactions".

Q3. **Do you use analogies in your research?** Select one

Q3b. **If you do use analogies in your research, how often do you generate original analogies?** Select one

Q3c. **If possible, can you offer an example of an analogy you use / have used in your research?**

Q3d. **If you don't use analogies in your research, is there a specific reason why you don't?**

4. Computer simulations.

Q4. **In your research, do you ever use computer simulations to help you visualize things?**

Select one

Q4b. **If so, can you please offer an example?**

Q4c. **If you don't use computer simulations to help you visualize things, is there a specific reason why?**

Q4d. **Do you think that computer simulations have strengthened physicists' visualization capabilities:**

In your own research area? Select one

In physics in general? Select one

Q4e. **Can you please elaborate on your choice in Q4d above?**

Q4f. **What, in your opinion, are the possible disadvantages of using computer simulation?**

5. Physics Communication.

Q5a. **How often do you communicate physics to the following groups?**

Colleagues (in your own research group) Select one

Peers (from a competing research group) Select one

Physicists from a different branch (e.g. an astrophysicist communicating with a condensed matter physicist) Select one

Scientists from a different discipline (e.g. biology, chemistry, geology, etc.) Select one

Post-graduate students. Select one

Graduate students who are considering doing a PhD in your research area. Select one

Undergraduate students. Select one

The general public. Select one

Other: please state:

Select one

Q5b. **Do you ever use analogies when communicating physics with the following groups?**

Colleagues (in your own research group) Select one

Peers (from a competing research group) Select one

Physicists from a different branch (e.g. an astrophysicist communicating with a condensed matter physicist) Select one

Scientists from a different discipline (e.g. biology, chemistry, geology, etc.) Select one

Post-graduate students. Select one

Graduate students who are considering doing a PhD in your research area. Select one

Undergraduate students. Select one

The general public. Select one

Other: please state:

Select one

Q5c. **Do the following factors influence your use of analogy when communicating with your target audience?**

Physics expertise of target audience. Select one

Prestige of occasion. Select one

Nationality of (majority of) target audience. Select one

Other: please state:

Select one

Q5d. **Could you please elaborate on your responses to Q5c above?**

Please type your brief elaboration in the cells below.

Physics expertise of target audience.

Prestige of occasion.

Nationality of (majority of) target audience.

Other: please state

Q6. **Would you be willing to offer additional insight on this topic**, by corresponding with me (just on one or two occasions) in the future? Select one

Preferred method of communication: Select one

Contact details

Email address: @

Q7. **Any additional comments are very welcome.**

Additional comments (if any):

Thank you very much for taking the time to fill out this questionnaire. Your kindness and patience are very much appreciated.

I will store contact details of all respondents, but anonymity will, of course, be guaranteed in the presentation of my findings.

Thank you again. Send email

End of Questionnaire.

A2.2 Summary of My Contact With Dr. John Lawson.

2003: Dr. Lawson wrote to me on 25-03-2003 after seeing my 'Letter to the Editor' in Physics World (Vol. p.). He enclosed 10 of his scientific papers (dating from 1950 to 1989) with post-it note annotations regarding his use of analogy, and remarked that he had noticed, in the course of his long and varied career, how research background and nationality affected physicists' use of analogy.

2003: I replied to Dr. Lawson on 04-04-2003, thanking him for his input. I explained that I was, at the time, in the process of analysing a large amount of questionnaire data and would like to carry out a case study of his work as a follow-up to this large-scale survey.

2004: On 15-01-2004 I visited Dr. Lawson at his residence. We carried out a 30-minute semi-structured interview and looked at his archive of published and unpublished notes.

2004: Dr. Lawson wrote to me concerning the issues surrounding Maxwell and Faraday's differing backgrounds as detailed in John Gribbin's book, Science: A History. He enclosed a photo-copy of the relevant passages.

2004: Having analysed Dr. Lawson's scientific papers, book and the transcript of our first interview, I formulated a list of pertinent questions and on 22-03-2004 conducted a 30-minute semi-structured telephone interview with Dr. Lawson in order to explore my hypotheses concerning the techniques he used to conceptualise and communicate physics.

2004: On 04-10-2004 Dr. Lawson returned a completed questionnaire sent by me on 15-08-2004. It details what he means by the term 'insight'.

2004: I sent Dr. Lawson a questionnaire on 14-11-2004 concerning the contexts in which he found certain conceptualisation and communication tools useful and the atmosphere in which he worked. I ask that he give me his responses by telephone at some point.

2005: We carried out a semi-structured interview by telephone on 13-01-2005 exploring the issues raised in the questionnaire of 14-11-2004.

2006: On 07-Jan-2006 I sent Dr. Lawson 3 draft chapters based on his work. After a cursory glance of the content of these chapters he agreed to waive his right to anonymity.

A3.1: Extract from my excel data-sheet, regarding questionnaire respondents comments on visualisation.

Respondent ID	Q1b. What is your present job title, occupation or course of study?	Q1c. Gender ?	Q1d. Age ?	Q1e. What are you present research interests?	Q2. Do you ever find it difficult to get a mental picture of the physical processes involved in your research?	Q2b. Why do you think this is?	Q2c. Where you do have difficulty, how do you overcome this?
Phys_26	Research Co-ordinator (Lecturer - Seconded)	Male	38	Physics of Molecular Materials - nonlinear optics/electronics -organic polymers, fullerenes, carbon nanotubes - applications of spectroscopy.	3	Not great with symmetry	Overcome by using models - trying to think from different approaches
Phys_76	Reader Atmospheric Physics	Male	43	Cirrus and thunderstorm clouds; Atmospheric flows; Aircraft observations of high altitude atmospehric processes; Surface Atmosphere Exchange of Gases and Aerosols; Cloud Aerosol Interactions; Cloud Microphysical Instrumentation; Micrometeorological Measurement Techniques Forest atmosphere exchange; Urban Meteorology and Aerosol; Aerosol Instrumentation	5	My thought processes are somewhat disorganised. Show me a tangent and I will off on it	I focus
Phys_14	Professor of Physics	Male	53	Physics and chemistry of thin film materials for electronics and photonics; compound semiconductors;epitaxial films; photoluminescence spectroscopy; copper metallization; electrodeposition; physical electrochemistry.	2	I believe that I have a good intuition for physical processes and naturally visualise them	Sometimes drawing rough diagrams helps. For complex 3-dimensional situations, 3-D models can be useful
Phys_19	Professor of Theoretical Physics	Male	This is an AGEIST question, but still: 60 years young	Atomic,molecular and optical and condensed-matter physics,occasionally nuclear. Notably:hevy-particle collision theory,Wannier above & below theshold phenomena and ferromagnetism,including fractals.	1	Excellent visuo-spatial iq	

Table A3.1: A selection of respondent comments regarding the degree to which they find it difficult to get a mental picture of the physical processes involved in their research, the reasons why, and the techniques they use to overcome their difficulties.

A3.2 Examples of Thought Experiments published in the areas of cosmology, general relativity and quantum gravity.
Suggested and explained by Phys_54 during follow-up e-mail exchanges in Jan 2006.

Let me give a couple of examples of though experiments in the literature:

1. The tethered galaxy problem.
One thought experiment (explored in E.R. Harrison, 1995, Astrophysical Journal 446, 63-66,"Mining energy in an expanding universe") is the question: Suppose I had a string (sufficiently long) stretched between two galaxies which are flying away from each other with the Hubble flow, i.e., with the expansion of the universe. If I held onto the string giving friction and heat, could I thereby extract energy from the expansion of the Universe, presumably thereby also slowing down the expansion of the Universe ever so slightly? This is an important conceptual problem, and thinking about it carefully helps one to understand the subtleties in the definition of energy in an expanding universe, even though the experiment itself is physically impossible. [Harrison is a well-known cosmologist, associated with the Harrison-Zeldovich spectrum of scale free primordial perturbations, which are believed to be those actually produced by cosmic inflation.]

2. Boxes of radiation lowered into black holes.
This thought experiment was introduced by Jakob Bekenstein in 1973, leading to a problem with a generalized version of the second law of thermodynamics, which was resolved by Bill Unruh and Bob Wald in W.G. Unruh and R.M. Wald, 1982, Physical Review D 25, 942-958, "Acceleration radiation and the generalized second law of thermodynamics" [The earlier references of Bekenstein are also in Physicsl Review D: J.D. Bekenstein Phys. Rev. D 7 (1973) 2333; D 9 (1974) 3292.]

The basic idea is that it is possible to lower a box on a string containing some radiation with a certain energy and entropy into a black hole. Once the box gets close to the black hole a shutter opens, and the energy and entropy of the radiation are absorbed by the black hole. After the entropy of the radiation is absorbed, the entropy of the system is just that of the black hole. It can be arranged that the increase in the entropy of the black hole is less than the entropy of the radiation that went in, seeming to give a violation of the generalized second law of thermodynamics. Together with the Hawking effect it would seem possible theoretically to create a perpetual motion machine. Bekenstein tried to resolve this by suggesting that there were physical limits on the amounts of energy and entropy you could dump into a black hole this way. However, the arguments were not satisfactory, as there were ways around it. Things can be resolved once the Hawking effect is taken into account properly since the pressure of the Hawking radiation emitted by the black hole gives an extra buoyancy force on the box, much like the buoyancy force of water on a submerged object which is the basis of Archimedes principle (and is taught in first year physics). Once you take this buoyancy force into account, then the work done in lowering the string is less, and the calculations are different in such a way that the generalized second law of thermodynamics still holds."

(Phys_54e. In an e-mail exchange with Ciara Muldoon, 17-01-2006)

A3.3 Four charts showing the extent to which respondents said they visualise different kinds of experiments.

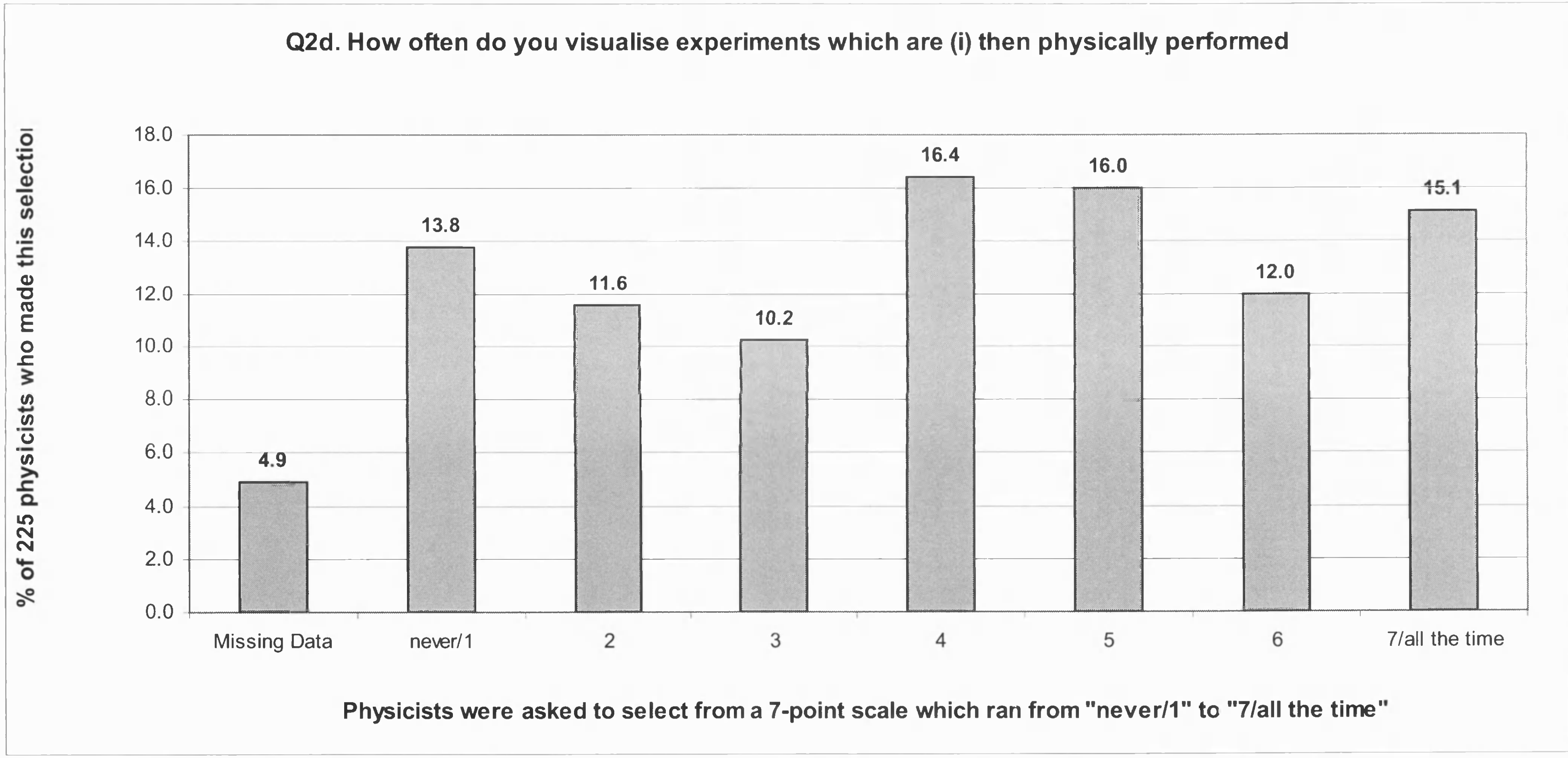

Figure A3.1: Degree to which respondents visualise experiments which are then physically performed, from Q2d of on-line questionnaire.

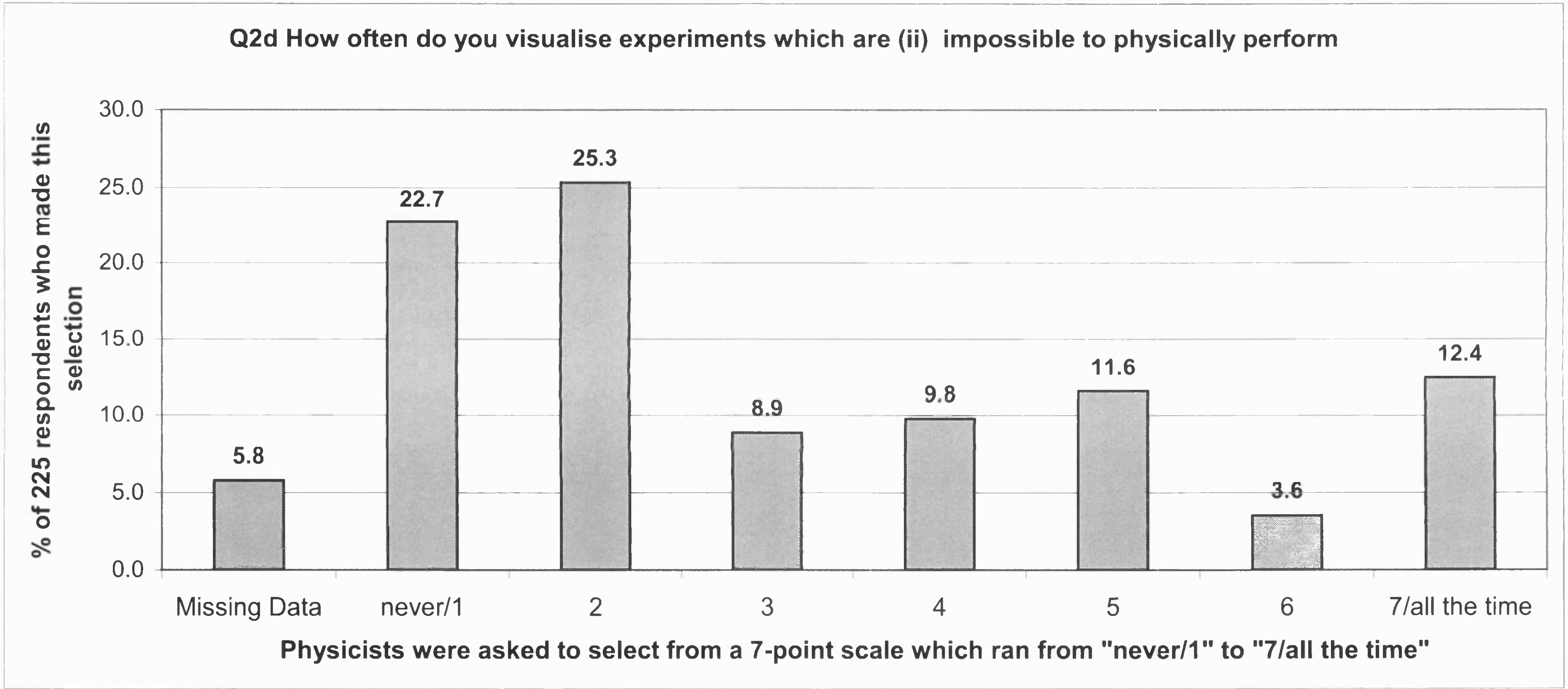

Figure A3.2: Degree to which respondents' visualise experiments which are impossible to physically perform, from Q2d of on-line questionnaire.

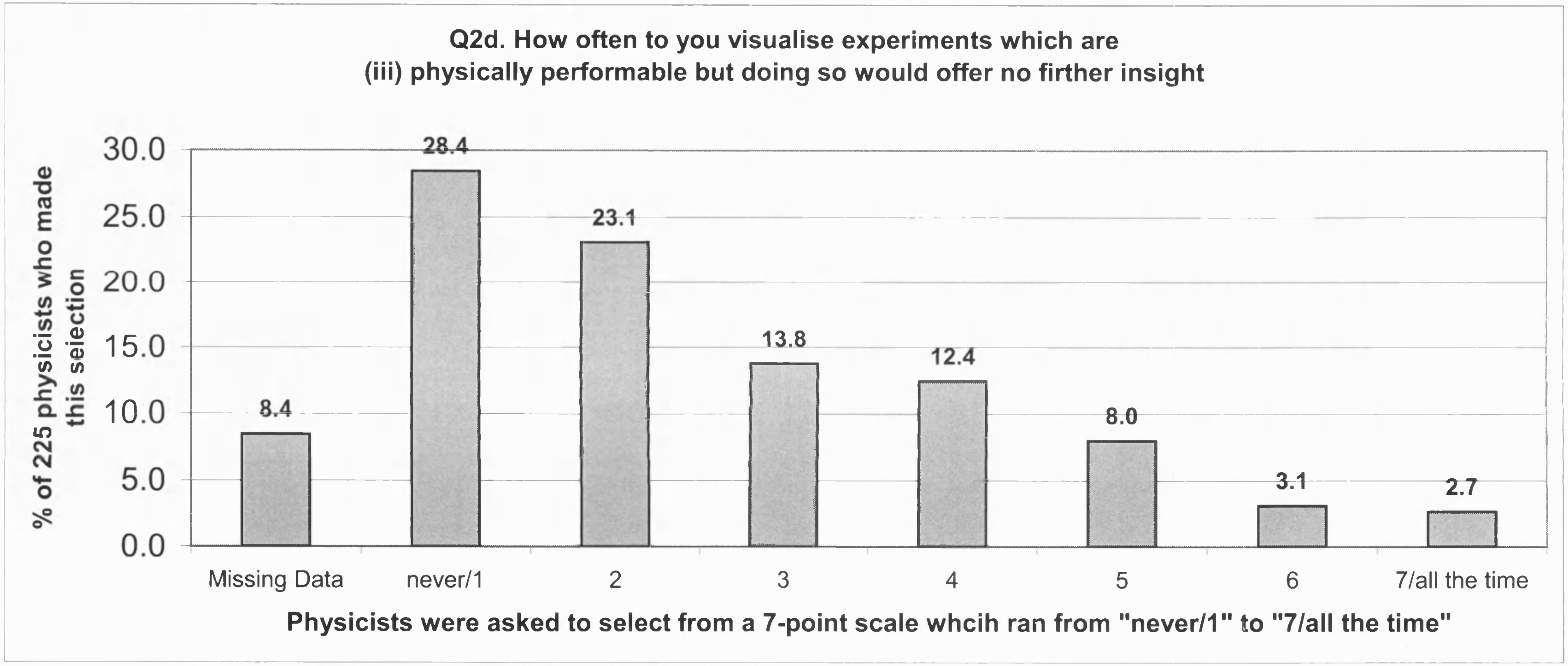

Figure A3.3: Degree to which respondents' visualise experiments which are physically performable but doing so would offer no further insight, from Q2d of on-line questionnaire.

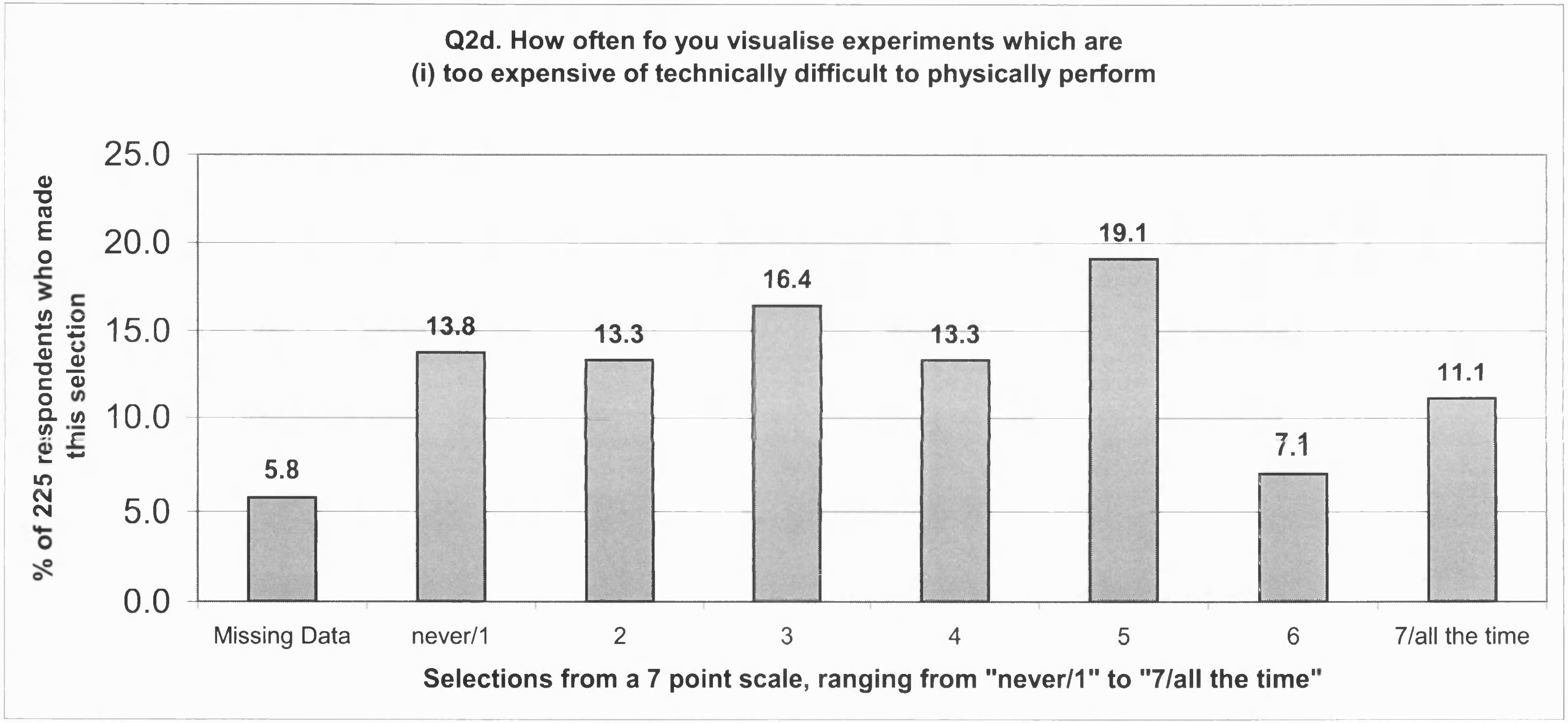

Figure A3.4: Shows the degree to which respondents' visualise experiments which are too expensive of technically difficult to physically perform, fro Q2d of the on-line questionnaire.

A4.1 Have computer simulations strengthened physicists' visualization capabilities (i) in their own research area & (ii) in physics in general?

(Related to chapter 4, section 4.5)

In Q4d respondents were asked: *"Do you think that computer simulations have strengthened physicists' visualization capabilities (i) in your own research area (ii) in physics in general?"* Respondents were then asked in question **4e** of the on-line questionnaire: ***"****Can you please elaborate on your choice in Q4d above?"*

A4.1.1 Selection of respondents who said that computer simulations "definitely have" strengthened physicists visualisation capabilities both in their own research area and in physics in general.

- **[7 & 7]**[1] "It is impossible to probe certain functions systematically without computers (this is not necessarily 'simulation' in the sense used by some physicists, but is definitely visualisation). Much of my research in fundamental physics (eg classical crystal optics, statistical geometry of stochastic functions) would have been impossible without computer visualisation techniques." **Phys_74**
- **[7 & 7]** "Modern visualisation tools allow us to interpret complex physical phenomena in a much more intuitive way as we don't first have to construct some plausible scenario in our mind first." **Phys_21**
- **[7 & 7]** "some of the work I do it on stars with nebulae around them - mass that is lost from a star, but not evenly all around it, rather directed along the magnetic north and south poles, or around some other axis. simulations from theoretical models of these outflows are extremely helpful in then producing from the modeled 3D shapes, the 2D shapes that would be observed(since when we look at something we only really see it in 2D), which are then compared with the images of these objects we gather with telescopes. D= dimensions." **Phys_22**
- **[7 & 7]** "In my own field we realised that some of our plasmas emitted x-rays longer when hit by a more intense laser, not becasue [sic] of the reduction sic] in recombination rate which intuition told us was the answer but because of a sustained collisional ionisation rate as revealed by simulation. This latter is a rather technical example." **Phys_25**
- **[7 & 7]** "In my field, computer simulations can be used to show the effect of relativistic motion of an astrophysical source of radiation, and to predict what would actually be observed. It is often not easy to predict what should be observed in any detail without some computer simulation work." **Phys_41**
- **[7 & 7]** "I can comment about our research area: we are dealing with extremely complex, multi-body systems, for which analytical solutions or treatment are of limited use. On the other hand computational codes (thanks to the ever increasing computer performances) can deal with demanding numerical calculations and provide visual outputs. In particular, in codes it is possible to switch on and off particular phenomena or effects and see their impact on the final results (which is not possible in experiments in most cases)." **Phys_43**
- **[7 & 7]** "Theoreticians have used simulations to visualize atomic-scale phenomena inaccessible directly- for example, the trapping of positrons in atom-sized open-volume defects in solids." **Phys_62**
- **[7 & 7]** "In astronomy, lots of data have more than two dimensions. Computers give the insight e.g. in the 3d-structure of a cluster, the velocity field of a galaxy or the time dependence of the galactic structures (formation/interaction)" **Phys_77**
- **[7 & 7]** "Spatio-temporal chaos and the formation of patterns; molecular structures; velocity fields in hemodynamics; optical interference patterns; atomic orbitals. The list is simply phenomenal." **Phys_99**
- **[7 & 7]** "I believe it is obvious." **Phys_101**
- **[7 & 7]** "In magnetism it is very hard to argue otherwise." **Phys_113**
- **[7 & 7]** "Allowing other disciplines to understand/visualise concepts. All branches of science interweave at some level. Communication and discussion is crucial to good science." **Phys_132**

[1] Numbers in square brackets indicate selections from the 7-point scale, from **"no, they definitely have not/1"** to **"7/yes, they definitely have."**

- **[7 & 7]** "Visualisation can make abstract mathematical models come alive. You perceive the mathematical solution in a way that taps into the very fundamental sense of sight and therefore perhaps utilise a large sub-conscious processing power that is not available from the purely abstract." **Phys_149**
- **[7 & 7]** "in complex systems our brains seem too small to be able to interpret big ugly equations into physical scenarios. to calculate specific examples is time consuming. computers can do calculations very fast and not hurt our heads. Seeing equations in action helps us understand their consequences better. Examples - nonlinear physics, chaos, helps see patterns ..." **Phys_177**

A4.1.2 Selection of responses suggesting that computer simulations <u>have not</u> strengthened physicists' visualisation capabilities in respondents' own research area and may or may not have in physics in general.

- **[1 & 1]** [2] "Visualisation is just a very nice marketing tool for physics. It came as well fitted to the visualisation of complex systems fractals and old classical physics recently extending into chaos theories (e.g. the celebrated Mandelbrot pictures) but visualisation is meaningless for n-dimensional spaces, Lie algebras in QM etc..." **Phys_79**
- **[1 & 7].** "[blank]" **Phys_105**
- **[1 & 1]** "The computer is a nice instrument but cannot replace human ingenuity. We have however to distinguish between 'visualisation' where the advent of computers has not changed much and 'simulation'. I do think that simulating complicated physical system is a genuinely new tool of scientific discovery." **Phys_165**
- **[1 & -]** "The ability however to plot or compute areas of the problem using packages, e.g. Mathematica, Maple, FORM, certainly have helped, otherwise see Q4c.A lot of work is done on lattice field theory, where one aims to compute results directly by simulating the fluctuating quantum fields. This does not contribute to visualization, but is beginning to make a serious contribution to getting numerical answers." **Phys_170**
- **[1 & 3]** "The reactions I carry out are fairly simple - no need to use a computer to visualise." **Phys_5**
- **[1 & 7]** "Mine is a simple concept, whereas some physics is not easily explained without simulations." **Phys_45**
- **[1 & 4]** "They have not benefited me because i have not used them. For Physics in general i just trust Simulation and Modelling as a useful aid." **Phys_225**
- **[2 & 7]** "Vision is only one of the ways in which we know the world. Its dominance at present is pedagological rather that fundamental." **Phys_115**

A4.2 Selection of Questionnaire Respondents' Written Responses Regarding The Reality Status of Computer Simulations.

(Related to chapter 4, section 4.6.4)

- **[1]** "Computer simulations can only suggest what *might* happen, this still has to be shown by experimentation. So long as people don't confuse a computer model and reality, there is no problem. Computer simulations are frequently just a more advanced, ie faster and more complex, analytical solution." **Phys_86**
- **[1]** "Promotion of a cartoon view of reality." **Phys_115**
- **[1]** "I think that scientist can forget that it's their job to understand what happens in nature. They do not make it happen, although they might contrive the conditions. Computers are powerful enough to disconnect the user from the real world." **Phys_132**
- **[1]** "It is hard to know to what extent they accurately reflect reality, and there is the possibility of being fooled by them." **Phys_162**
- **[1]** "I do not believe that modelling is sufficiently near to reality to be of value. It is only as good as the model used and most real life physical systems are much more complex than the model can

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[2] The numbers inside the square brackets indicate respondents' selections from the 7-point scale on whether computer simulations have strengthened physicists visualisation capabilities (i) in their own research area & (ii) in physics in general.

handle in a reasonable amount of time. In my experience, the (mathematical) modellers have followed what I/we have done and not lead us." **Phys_200**

- [2] "Care needed in setting up the simulation to make it represent reality. Experimental checks are needed" **Phys_121**
- [3] "the fact that the computer can only simulate based on what you tell it, and you don't necessarily know enough to make the model have any basis in reality" **Phys_164**
- [3] "In general - substitution of the real world by a virtual reality. It is very easy to lose the link with the real experimental results..." **Phys_168**
- 4] "Treating data from simulations as real. Unphysical approximations or mathematical fiddles being used to make the simulation 'fit' the data rather than understanding the physics behind what is going on." **Phys_88**
- [4] "Some things which could happen in reality may be too complex to easily code." **Phys_146**
- [4] "Disadvantage - to mistake the model for the 'truth'. This has always been a danger of any model (ie any approximation), including Newton's mechanics and Einstein's special relativity." **Phys_217**
- [5] "You have to remember it is only a model or simulation and that reality probably is different." **Phys_167**
- [5] "neglect of real world factors. It's all too clean and there's never any noise effects, random errors etc. My modelled radiative transfer always looks clean and noise free, whereas real measurements are noisy and have offsets, instrumental effects and interferences and bad hair days!" **Phys_211**
- [6] "Lose contact with reality and with what is actually do-able." **Phys_138**
- [7] "Too much reliance on them will remove people from the reality." **Phys_98**
- [7] "That you start to believe the simulations are 'real'." **Phys_135**
- [7] "It's not 'real' physics. You must always be careful to make it as physically realistic as possible." **Phys_136**
- [7] "A computer simulation can only be an approximation to the real world so it is important to really know what the quantitative effects of the approximations are." **Phys_212**

A4.3 Selection of Questionnaire Respondents' Written Comments Regarding The importance of establishing of the empirical reliability of models in a methodologically accepted way. (Related to section 4.6.4)

- "Getting your simulation to match with the <u>experimental results!</u> You have to fold in the uncertainties and this often requires estimations or fitting to data. You don't always understand why you need the correction you do." **Phys_51**
- "The real world is always right, only the interpretation of results can be wrong. In a simulation the virtual world can easily be wrong. In the end <u>real experiments</u> are always necessary." **Phys_53**
- "do you believe the model? - it has to be tested against <u>experiment.</u>" **Phys_58**
- "Over-emphasis: lack of linkage between simulation and <u>experiment.</u>" **Phys_62**
- "It is too tempting to use simulation instead of <u>real experiments</u> for teaching. My feelings say that it is very important for a physicist to have experience with nature directly rather than using simulations, which deliver an idealized view of the things." **Phys_77**
- "It is highly dependant on <u>experimental</u> results and also on how the **experiment** was conducted. A good calculation needs to be coordinated with experimentalists but unfortunately most experimentalists don't understand the computation methods well enough probably because they are convinced they can do without computations." **Phys_105**
- "Care needed in setting up the simulation to make it represent reality. <u>Experimental checks</u> are needed" **Phys_121**
- "They can become so detailed, trying to include all the warts and wrinkles, that the essential elements become lost in the details. Also, how do we test some of these models? That is an important element. Computer models are NOT <u>"experiments"</u> as some have described them, and the results are NOT "data"." **Phys_202**

A5.1: Examples of analogy provided by questionnaire respondents who indicated that they use analogy "7/all the time" in their research. (With Reference to Chapter 5, Section 5.2)

Of the 52 physicists that claimed to use analogy "all the time" in their research, 40 physicists provided exemplary analogies. These are listed below.

- "Polarisation flipping in lasers describes using potential wells similar to ball on a hill." **Phys_2**
- "I used analogies for explaining thermal stress generation generated by laser beams with the equivalent size of a mechanical object striking a surface. For example if 100w of laser light is foussed to a very small spot size, it imparts a high thermal stress to the surface, as the power density (power per unit area) is high. Equally if a very sharp and fine object is projected at high velocity at a surface it will impart a high stress. The same analogy holds for a large spot laser beam and a large blunt mechanical object imparting a lower stress on a surface which it is striking." **Phys_4**
- "particle sliding on the surface of a tapering cone so that the azimuthal angle is arbitrary for forward scattering" **Phys_19**
- "football formations (e.g. 4-4-2) and levels and states in atoms" **Phys_24**
- "Quanta of energy in quantum mechanics as a cent of euro in monetary system" **Phys_28**
- "Thinking of waves like water" **Phys_31**
- "I develop analogies through mathematics and not from visual experiments" **Phys_37**
- "Analogy of a financial market with molecules in a gas" **Phys_40**
- "various in the areas of electricity and radioactivity." **Phys_46**
- "current as analogous to water flow" **Phys_49**
- "A dislocation in a crystal is like an elastic band in free space." **Phys_50**
- "Curvature of spacetime in terms of masses stretching a rubber sheet, and motions of test particles on such a sheet is a standard analogy which is useful for thinking about geometry near black holes, and one which I use a lot in lectures." **Phys_54**
- "Pipe resonances and the geometry of bays behind breakwaters" **Phys_57**
- "trapping of ions in potential wells" **Phys_57**
- "Modelling electron transport through nanocrystalline TiO2 as 'hoppers' walking randomly through a cubic lattice" **Phys_69**
- "strongly correlated electrons as localised particles" **Phys_71**
- "Optical phase singularity = singularity of time zone at the north pole = singularity on lattice in crystal dislocation" **Phys_74**
- "Electric current <--> Flux of fluid; CCD detector array <--> Array of buckets collecting rain; Optical wavefront <--> Pressure wave (becomes e.g. compressed when moving to higher index medium)" **Phys_77**
- "The comparison of the generalized Ramsauer-Townsend effect with Fresnel scattering of optics" **Phys_78**
- "quantum vacuum fluctuations impinging on a moving reflective surface are like walking through the rain - one picks up much more rain on one's front than on one's back" **Phys_81**
- "Looking at a system through some number of slits in order to gain some course grained resolution and in order to make measurements on that system in such a way as to not cause it to collapse into one particular state. Sorry - this is slightly vague - basically a way to perform more subtle quantum measurements." **Phys_96**
- "Seabed volcanoes are pustules on the Earth's skin ?" **Phys_98**
- "magnetically ordered parts of the globally disordered system under study behaved similarly to the solid pieces (islands) in a liquid." **Phys_113**
- "Classical localisation of excitons in disordered solids." **Phys_115**
- "phonon - coupled electric oscillators" **Phys_116**
- "It is well known that polar organic material on water surfaces often acts as a surfactant, conversely an organic particle may be processed by oxidation in the atmosphere to allow it to take up water and so act as a cloud condensation nucleus. This is potentially important but has not yet been shown to be important in the atmosphere. A resistance analogy for the uptake of gases and particles by plant canopies" **Phys_117**

- "Well, I always deal with electromagnetic fields by thinking about field lines as bits of thick rubbery stuff -- resist being stretched, and are mutually repulsive." **Phys_119**
- "The analogy of the gravitational mass quadrupole moment of a body, and its tensor of inertia." **Phys_120**
- "Modelling colloidal particles as point like massive particles which diffuse. Model reaction-diffusion systems by point size particles which diffuse, multiply and die" **Phys_124**
- "The black hole resembles a space-time river racing towards a water fall, Singularity Falls. Picture a river with fish that have a maximal velocity, say c. If the river flows faster than c the fish are swept away." **Phys_128**
- "That photons can behave as either 'particles' or 'waves'" **Phys_135**
- "Electrical circuitry to understand heat flow. "Domestic" Water supply to explain an electrical circuit. Stretched rubber sheet as analogue of Poisson/Laplace's equations." **Phys_150**
- "The expansion of the universe like a ball thrown in a gravitational field" **Phys_152**
- "Quantum Hall Effect for AC current could (I am not sure, it is unpublished) be explained in terms of a charge wave motion with a constant (rather low) speed along the edge of the sample (as usually it is Hall bar) from one contact to another clockwise or anticlockwise depending on the direction of magnetic field." **Phys_168**
- "They're too numerous and not often very pictorial. Thus often the research progresses by noticing that the problem "is like" another problem in some respects and thus the outcome might be expected to be similar. If you can draw enough such analogies you can often have a good idea about what to expect even if the problem is not yet well defined or the calculation started. In other words, the analogies, for me at any rate, are typical of the Sheldon Glashow quote you give above rather than the more easily graspable earlier ones. Two I use at the moment: to regard the exact renormalization group as a continuum analogue of blocking on a lattice; to regard exact renormalization group as a form of reparametrization of an integral (the partition function integral). I would not be surprised if that means little to almost everyone! Feynman said that a good theoretical physicist should have at least three ways of looking at (or was it deriving?) something, on the grounds that just one of these might suggest a new approach. That is, more or less, what I strive for." **Phys_170**
- "The short distance structure of a photon which is due to vacuum fluctuations involving quarks and anti-quarks, and a similar approach for colour singlet exchange in bulk hadron physics" **Phys_174**
- "In quantum information we value entanglement between two seperate parties as a commodity - in some sense it is entanglement (particuliar to quamtum mechanics) that offers quantum computation and communication its power over classical analogies. given a pair of particles, we then would like to know how much entanglement they poses. This is a very tricky thing to define. One way to define such a measure is to see how much "maximal entanglment" (which we can easily define) it takes to create the pair. This is called entanglement of formation. Another measurement is defined by imagining we have an infinite supply of these particles and asking how much maximal entanglement it takes per particle pair ON AVERAGE. This is called the entanglement cost - or assymptotic entanglement of formation. The assymptotic measurement can in principle be lower that the one off measurement. The assymptotic measure is analogous to the whole sale price for purchasing, for example cars, which can give a lower cost per car than if one where to buy one alone. This analogy seems to help people understand the differnece..." **Phys_177**
- "Electron flow through a gated HFET device - constricted water-pipe analogy" **Phys_187**
- "Magnetic fields in fluids can be visualised as strings moving with the fluid" **Phys_196**
- "optics and quantum mechanical superposition" **Phys_197**
- "Traversal of a light beam around a laser cavity as a billiard ball around similar shaped cavity/table." **Phys_215**
- "One analogy I constantly use is the analogy of a superconducting island with a large, finite quantum spin. The phrase 'analogy' may not be quite right: In this case, the analogy is not of the form 'this is quite similar to' but rather of the form 'The maths of this situation is exactly the same as this situation; therefore physical intuition or visualisation of one situation maps directly to the other situation'" **Phys_221**

Respondents were asked to say with which of the 12 IoP groups (listed below) they would associate themselves.	Part 1: Shows # of physicists who associated themselves with this # of IoP group/branch. (Respondents selected a minimum of 1 group and maximum of 8 groups)								Part 2: Total # of physicists who associated themselves with this group	Part 3: Shows # of physicists who associate themselves with this # of the 12 IoP groups/branches as a % of the total number who associated themselves with this IoP group. (i.e. figures in part 1 divided by figures in part 2)							
	1	2	3	4	5	6	7	8		1	2	3	4	5	6	7	8
Applied Optics	4	8	13	8	4	4	2	0	43	9.3	18.6	30.2	18.6	9.3	9.3	4.7	0.0
Chemical Physics	0	4	8	8	5	2	1	0	28	0.0	14.3	28.6	28.6	17.9	7.1	3.6	0.0
Computational Physics	0	5	23	14	8	3	1	1	55	0.0	9.1	41.8	25.5	14.5	5.5	1.8	1.8
Surface Science & Technology	1	1	5	5	4	2	1	1	20	5.0	5.0	25.0	25.0	20.0	10.0	5.0	5.0
Nuclear Physics	4	3	4	3	1	1	1	1	18	22.2	16.7	22.2	16.7	5.6	5.6	5.6	5.6
Plasma Physics	2	1	9	9	1	1	0	1	24	8.3	4.2	37.5	37.5	4.2	4.2	0.0	4.2
Condensed Matter & Material Physics	11	11	18	14	7	4	2	1	68	16.2	16.2	26.5	20.6	10.3	5.9	2.9	1.5
High Energy & Particle Physics	11	11	7	3	1	2	1	1	37	29.7	29.7	18.9	8.1	2.7	5.4	2.7	2.7
Mathematical & Theoretical Physics	6	13	20	15	6	3	1	1	65	9.2	20.0	30.8	23.1	9.2	4.6	1.5	1.5
Spectroscopy	1	5	11	8	8	3	1	0	37	2.7	13.5	29.7	21.6	21.6	8.1	2.7	0.0
Quantum Electronics & Photonics	3	5	9	11	7	2	2	1	40	7.5	12.5	22.5	27.5	17.5	5.0	5.0	2.5
Astrophysics	21	10	16	6	5	2	0	0	**60**	**35.0**	16.7	26.7	10.0	8.3	3.3	0.0	0.0

Table A5.1: Quantitative data regarding the number of groups with which respondents associated themselves. See for example, that of the 60 respondents who associated themselves with Astrophysics, 35% associated themselves with no other group.

A6.1 Degree to which academic status or prestige of occasion influences respondents' use of analogy. (Relevant to section, 6.6).

Tables A6.1 – A6.5 on the following pages contain noteworthy responses regarding the degree to which respondents' use of analogy is influenced by the academic status of their audience or the prestige of the occasion. For the first 50 responses, the question read: "Does **academic status** influence your use of analogy when communicating with your target audience?" The notion of academic status was seen to be identical to expertise for some respondents, so in an attempt to clarify matters, from response 50 to 225 the question read: "Does **prestige of occasion** influence your use of analogy when communicating with your target audience?" This turned out to be just as confusing for many physicists. However some respondents did suggest that they would use better analogies on more prestigious occasion. This is shown in Table A6.1 below.

Table A6.1: Shows that on prestigious occasions some physicists would use analogy to the same extent or make an effort to generate good analogies.

ID	Age	Q5c. Does academic status/ prestige of occasion influence your use of analogy when communicating with your target audience? (1=not at all; 7 = very much so)	Q5d. Could you please elaborate on you choice in Q5c above?
Phys_55	24	3	"In a more prestigious situation, I would be more tempted to use analogy, to demonstrate by ability at coming up with analogies!"
Phys_68	44	1	"I find that even amongst distinguished colleagues it is better to give a picture that everyone can understand. I have seen this done by the most eminent in the field, and everyone appreciates that they can understand what is going on."
Phys_114	59	4	"A prestigious occasion makes me work harder to try to think of an analogy."
Phys_160	52	1	"Regardless of the prestige of an occasion, I think that I will make the most useful and favourable impression on an audience by explaining myself clearly. What counts is (my perception of) the background and expertise of the audience. In my experience, no audience feels patronized by the substitution of an appropriate analogy for the 'real thing'."
Phys_165	36	2	"Might have a small effect. People tell me that the most silly jokes should be omitted in more prestigious occasions and that the pictures should look more fancy."
Phys_198	32	2	"come up with good analogies for a more prestigious occasion."
Phys_207	25	6	"If at a major conference or occasion, a new analogy is often preferred to repeating a 'classic' analogy."

A7.1 Outline of J.D. Lawson's Career:

04-April-1923: Date of birth.

1920s-1930s: John Lawson's abilities as an "engineer stroke physicist" were evident from an early age. He told me in our first interview:

> "I regard myself as a sort of engineer stroke physicist, I think. I mean as a boy, I was always making things,...usually I had no resources, because we weren't very well off and it was a question of using bits and pieces of anything else, and scrounging...which was very good for me really..." [3]

1943: Emerged from Cambridge with a 'wartime' degree in mechanical sciences, which included electrical engineering and radio, as a preparation for radiolocation (radar) research.

1943: Started his career at **T**elecommunications **R**esearch **E**stablishment (TRE) Malvern: Micro Wave Aerials Group, where he worked on airborne radar.

1947: Joined **A**tomic **E**nergy **R**esearch **E**stablishment (AERE) Malvern Branch: Accelerator group.

1951: Transferred to AERE Harwell General Physics Division [HQ of the **U**nited **K**ingdom **A**tomic **E**nergy **A**uthority (UKAEA)]

1951: Was at Harwell, leading the team developing the X-band Klystron.

1952: Made an important theoretical contribution to accelerator theory by his identification of resonances in strong focussing synchrotrons. As he explained to me:

> "[A]s the alternating gradient strong focusing machine was first presented, they'd not taken into account the possibility of orbital resonances, which make it very much more critical. And we [Dr. Lawson plus two colleagues] wrote a paper..." [4]

1955: Dr. Lawson turned his attention to fusion power.

> "The survey in to the problem of fusion power which he undertook in 1955 whilst at Harwell produced the now famous 'Lawson Criterion' governing energy 'breakeven' in thermonuclear power generation." [5]

1957: Derived the *Lawson Criterion* [6]

1961: Joined Rutherford Laboratory;

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[3] Dr. Lawson, speaking during our first interview at his residence, 14:30-15:00, 15-January-2004

[4] Dr. Lawson, speaking during our first interview at his residence, 14:30-15:00, 15-January-2004

[5] Rutherford Appleton Laboratory Bulletin, number 5, 6-Apil-1988, on the occasion of Dr. Lawson's election as an FRS.

[6] Wikipedia, the free on-line dictionary, has an entry for this term. It says: "In nuclear fusion research, the **Lawson criterion**, first derived by John D. Lawson in 1957, is an important general measure of a system that defines the conditions needed for a fusion reactor to reach **ignition**, that is, that the heating of the plasma by the products of the fusion reactions is sufficient to maintain the temperature of the plasma against all losses without external power input. As originally formulated the Lawson criterion gives a minimum required value for the product of the plasma (electron) density n_e and the "energy confinement time" τ_E. Later analyses suggested that a more useful figure of merit is the "triple product" of density, confinement time, and plasma temperature T. The triple product also has a minimum required value, and the name "Lawson criterion" often refers to this inequality."
(Source: http://en.wikipedia.org/wiki/Lawson_criterion Accessed 23-01-2006)

1969: Received his Sc.D. Physics (also at Cambridge);

1971: Elected fellow of the **Institute of Physics**;

1975:

"In **1975** because of his "rather unique" understanding of the physics of plasmas, his services were sought by Culham Laboratory where he spent two years on a design study of a conceptual fusion power reactor based on the 'reverse field pinch' principle, a development arising from the original ZETA experiment, establishing firmly where the limitations in current understanding of the underlying physics lay and providing guidelines for future strategies in this field." [7]

Dr. Lawson said to me that:
"A lot of my ideas were in showing how things wouldn't work as they were being claimed, especially with new things." [8]

1977: Publication of first edition of his **book, "The Physics of Charged Particle Beams,"** part of an International Series of Monograph in Physics, Oxford.

"A study in depth of problems of high intensity beams with the objective of integrating material from widely scattered fields (microwave tubes, electron optics, accelerators, plasma physics etc.) and providing a general unified treatment, was published in 1977 as an 'International Monograph in Physics' by the Clarendon Press. 'The Physics of Charged Particle Beams' has since had numerous reprints and been translated into Russian and, perhaps the ultimate accolade, into Chinese!" [9]

1985: Received **Thomas Young Medal** from the Physical Society, given for Optics.

1987: Retired from the Rutherford Appleton Laboratory. The RAL director, Paul Williams, said in an RAL Bulletin describing the occasion:

"To say he will be missed is the understatement of the year...We have learned to trust and respect his council and, so that we do not lose touch, have invited him to become one of the RAL's Honorary Scientists." (RAL Bulletin, 02-Nov-1987)

1988: Elected a Fellow of the Royal Society;

1988: Publication of the 2nd edition of his book *The Physics of Charged Particle Beams.*

1946-1997: Dr. Lawson has close to 100 formal journal publications including:
Journal of the Institute of Electrical Engineers; Nature; Philosophical Magazine; British Journal of Applied Physics; Nucleonics; Journal of Electronics and Control; Journal of Nuclear Energy; Radio and Electrical Engineering; Nuclear Instruments & Methods in Physics; American Journal of Physics; Journal of Scientific Instruments; IEEE Transactions on Nuclear Science; Physics Letters; Particle Accelerators; Contemporary Physics; Physics of Fluids; Plasma Physics; Advanced Electronics and Electron Physics; Annual Review of Nuclear Science; European Journal of Physics; Plasma Physics and Controlled Fusion;

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[7] Rutherford Appleton Laboratory Bulletin, number 5, 6-April-1988, on the occasion of Dr. Lawson's election as an FRS

[8] Dr. Lawson, speaking during our first interview at his residence, 15-Jan-2004

[9] Rutherford Appleton Laboratory Bulletin, number 5, 6-April-1988, on the occasion of Dr. Lawson's election as an FRS

A7.2 Interdisciplinary Electrical Analogies:

General	Electrical	Mechanical Translational	Mechanical Rotational	Hydraulic (Acoustic)	Thermal
Flow Variable (through variable)	Current, $I = \mathrm{d}q/\mathrm{d}t$ [Amps]	Force, F [Newtons]	Torque, T [Newton meters]	Volume (fluid) flow, G [m³/s]	Heat flow, q [Joules/sec]
Potential Variable (across variable)	Voltage, V [Volts]	Velocity, v [m/sec]	Angular velocity, ω [radians/sec]	Pressure drop, p [Pascals]	Temperature difference, T [°C]
Integrating Element (Delay Component)	Inductance, L [Henrys] Faraday's Law: $I = \int V\,\mathrm{d}t / L$	Elasticity Hooke's Law: $F = k \int v\,\mathrm{d}t$ k = spring constant (stiffness)	Elasticity (*e.g.*, torsion bar or coil spring) $T = k \int \omega\mathrm{d}t$ k = torsional spring constant	Inertance, M $G = \int p\,\mathrm{d}t / M$ *e.g.*, for pipe: $M = \rho L/A$	Not Applicable
Proportional Element (Dissipative Component)	Resistance, $R = \rho L/A$ [Ohms] Ohm's Law: $I = V/R$	Viscous friction (*e.g.*, dashpot or damper) $F = B\,v$ B = damping constant	Viscous friction $T = D\,w$ D = damping factor	Fluid resistance, R $G = p / R$	Heat transfer resistance, R $q = T / R$ $R_{convect} = 1/(h\,A)$
Differentiating Element (Accumulative Component)	Capacitance, $C = \varepsilon A/d$ [Farads] $I = C\,\mathrm{d}V/\mathrm{d}t$	Mass (*i.e.*, inertia), m [kg] Newton's Second Law of Motion $F = m\,\mathrm{d}v/\mathrm{d}t$	Polar Moment of Inertia, J $T = J\,\mathrm{d}\omega/\mathrm{d}t$	Fluid capacitance, C $G = C\,\mathrm{d}p/\mathrm{d}t$	Thermal heat capacity, $m\,c_p$ $q = m\,c_p\,\mathrm{d}T/\mathrm{d}t$
Other Variables	Charge, $q = \int I\,\mathrm{d}t$ [Coulombs]	Displacement, $x = \int v\,\mathrm{d}t$	Angle, $\beta = \int \omega\mathrm{d}t$	Flow velocity, $u = G/A$ [m/s] Volume, $V = \int G\,\mathrm{d}t$ [m³]	Heat, $Q = \int q\,\mathrm{d}t$ [Joules]
Junction/Node Law Σ(Flow) = 0	Kirchhoff's Current Law $\Sigma I = 0$	d'Alembert's Principle $\Sigma F = 0$	Second Law of Rotational Mechanical Systems $\Sigma T = 0$	$\Sigma G = 0$	$\Sigma q = 0$
Closed Loop Law Σ(Potential) = 0	Kirchhoff's Voltage Law $\Sigma V = 0$	Continuity of Space Law $\Sigma v = 0$	$\Sigma \omega = 0$	$\Sigma p = 0$	$\Sigma T = 0$
Power = (Potential)(Flow)	$P = I\,V$ [Watts]	$P = F\,v$	$P = T\,\omega$	$P = G\,p$	$P = T\,q$ [Watts °C]
Kinetic Energy	$E_k = ½\,L\,I^2$ [Joules]	$E_k = ½\,m\,v^2$	$E_k = ½\,J\,\omega^2$	$E_k = ½\,M\,G^2$	Not applicable
Potential Energy	$E_p = ½\,q^2/C$ [Joules]	$E_p = ½\,k\,x^2$	$E_p = ½\,k\,\beta^2$	$E_p = ½\,[\int G\,\mathrm{d}t]^2 / C$	Not applicable

Table A7.1: Electrical circuit analogies for several engineering disciplines have been developed over time. These are summarized in the table below prepared by Dr. Holbert. (Source: http://www.eas.asu.edu/~holbert/analogy.html ; Accessed: 26-01-2006).

A7.3 Dr. Lawson's preference for form, pattern and structure: Eg 2

Particle-Photon Interactions
Dr. Lawson.
CERN Accelerator School 'Synchrotron Radiation and Free Electron Lasers', Chester, April 1989.
Published in **CERN 90-63, 237, 1990.**

"This paper is concerned not with presenting techniques for making calculations or solving problems, but rather introducing a physical viewpoint which enables the relation between a range of different phenomena to be seen. In neighbouring fields of physics many different points of view and modes of description have evolved. Discussion of new developments and evaluation of new suggestions is greatly facilitated if one is familiar with different perspectives, different ways of thinking, and the relation between them."

"Again a wide range of phenomena looked at from a simple common viewpoint. (I was challenged to write a similar paper with only one equation! See European Jnl of Physics 5 p104 1984)" [10]

This is another instance where Dr. Lawson attempts to acquire or promote physical insight through utilising a table to facilitate cross comparison between "perspectives". A physicist with expertise in particle physics or astrophysics would be able to compare the plots and see that "clearly bremsstrahlung and Cherenkov radiation cannot be disentangled." [11]

Fig 9 Radiation of a single frequency component from a highly relativistic particle moving along a straight trajectory for various situations. The first column illustrates the current distribution associated with frequency ω_0. The second shows the spectrum of values of $\cos\theta$; this is a δ-function for an infinite path, but has finite width when the track is of finite length, corresponding to an electron which suddenly starts or stops. The third column shows the angular distribution of radiation observed at a great distance from the track. It corresponds simply to the radiation intensity, given by the square of the product of the distribution in the second column multiplied by $\sin\theta$. This is a polar plot, showing only real values of θ.

The first line corresponds to Cherenkov radiation from an infinite path in a dielectric medium, and the second to the 'unphysical' radiation consisting of virtual photons only from an electron in free space. The third example is the spectrum corresponding to an electron traversing a long track which is suddenly stopped. Strictly the second curve is the envelope of a very rapidly varying $(\sin x)/x$ function. The third and fourth curves correspond to electrons moving along a track of length L, corresponding to $N = \omega_0 L/2\pi\beta c$ wavelengths, and the shape can be considered as being determined by interference of the radiation from the two ends. The interesting point here is that there is clearly no sharp distinction between the first example in a dielectric where $n\beta > 1$ and the second, which could be in a dielectric or free space where $n\beta < 1$. Clearly bremsstrahlung and Cherenkov radiation cannot be disentangled. The final curves refer to a very short track, which produces dipole radiation.

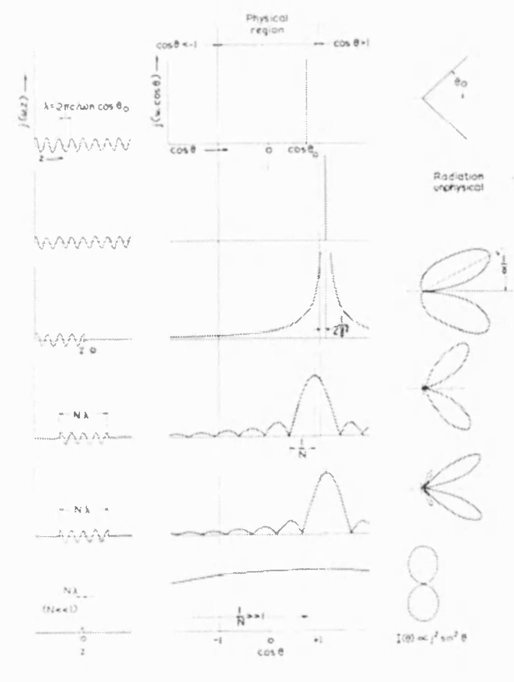


Figure A7.2: Lawson, Dr. (1989), *Particle-Photon Interactions*, p.14.

Appeared in CERN 90-63, 237, 1990.

[10] Dr. Lawson, annotation to paper, enclosed in with March 2003 letter to Ciara Muldoon
[11] Note: Bremsstrahlung radiation (German for "braking radiation"), is electromagnetic radiation produced when charged particles decelerate while passing through matter. Cherenkov radiation is electromagnetic radiation emitted when particles pass through a medium at a speed in excess of the speed of light in that medium. Cherenkov radiation produces the characteristic blue glow in nuclear reactors. Pavel Alekseyevich Cherenkov, winner of the 1958 Nobel Prize was the first to study it in detail and thereby gave his name to it.

A7.4: Dr. Lawson's preference for form, pattern and structure: Eg. 3

Some calculations on the pumping of trapped volumes.

J D Lawson, Rutherford High Energy Laboratory, Chilton, Berks

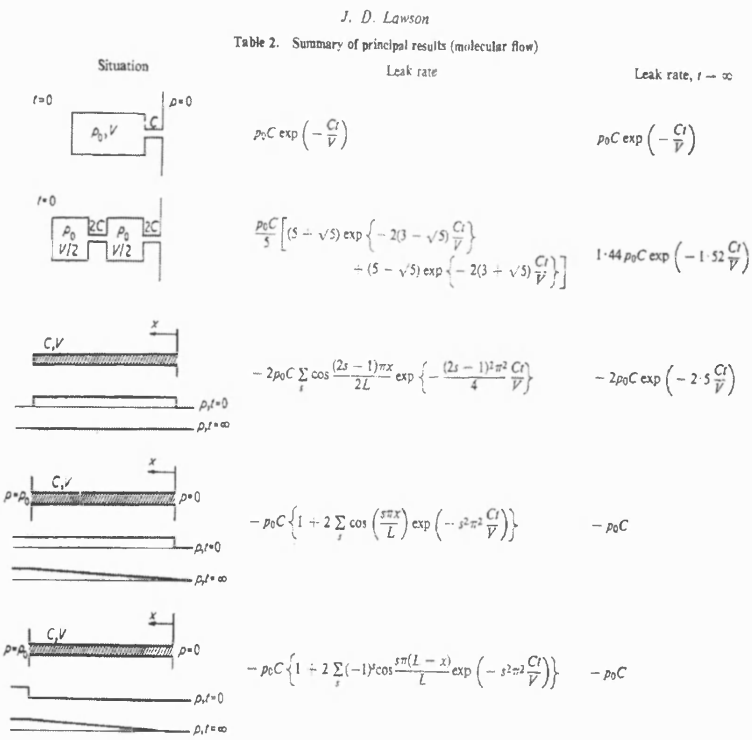
Received 16 December 1965. Published in **J. Sci. Instrum. 43 (August 1966) 565-568**

Abstract. Calculations are made of the pressure variation in, and mass flow out of, cavities containing air which are connected by low conductance leaks to an evacuated vessel. For a simple system, consisting of one cavity, both viscous and molecular flow are considered, but for more complicated configurations attention is confined to molecular flow. Values of leak conductance which give the highest flow rate after a fixed pumping time are calculated for both molecular and viscous flow for the simple single cavity configuration. The principal results are tabulated as a set of formulae, judicious use of which should enable order of magnitude calculations to be made over a useful range of configurations.

Introduction:

"…The approach in this paper is purely phenomenological. Since a precise application of the results is unlikely, simplifications of the basic formulae are made; the gain in clarity thus obtained for outweighs the loss of accuracy of some 25% which results…"

Again, Dr. Lawson employs a tabular format to compare leak rates with different cavity configurations, i.e. different physical situations. This is intended to provide the reader with (physical) insights. Dr. Lawson defends this approach saying that, "the gain in clarity thus obtained for outweighs the loss of accuracy…"



J. D. Lawson

Table 2. Summary of principal results (molecular flow)

Situation	Leak rate	Leak rate, $t \to \infty$
	$p_0 C \exp\left(-\frac{Ct}{V}\right)$	$p_0 C \exp\left(-\frac{Ct}{V}\right)$
	$\frac{p_0 C}{5}\left[(5+\sqrt{5})\exp\left\{-2(3-\sqrt{5})\frac{Ct}{V}\right\} + (5-\sqrt{5})\exp\left\{-2(3+\sqrt{5})\frac{Ct}{V}\right\}\right]$	$1{\cdot}44\, p_0 C \exp\left(-1{\cdot}52\frac{Ct}{V}\right)$
	$-2p_0 C \sum_s \cos\frac{(2s-1)\pi x}{2L}\exp\left\{-\frac{(2s-1)^2\pi^2}{4}\frac{Ct}{V}\right\}$	$-2p_0 C \exp\left(-2{\cdot}5\frac{Ct}{V}\right)$
	$-p_0 C\left\{1+2\sum_s \cos\left(\frac{s\pi x}{L}\right)\exp\left(-s^2\pi^2\frac{Ct}{V}\right)\right\}$	$-p_0 C$
	$-p_0 C\left\{1+2\sum_s (-1)^s \cos\frac{s\pi(L-x)}{L}\exp\left(-s^2\pi^2\frac{Ct}{V}\right)\right\}$	$-p_0 C$

Figure A7.3: Lawson, Dr., (1965), *Some calculations on the pumping of trapped volumes*, p. 568 In **J. Sci. Instrum**. 43 (August 1966) 565-568

A7.5 Dr. Lawson's preference for form, pattern and structure: E.g. 4

Optical and Hydrodynamical approaches to charged particle beams.
Dr. Lawson, Rutherford Lab., Chilton, UK

Published in **Plasma Phys. 17 (July 1975) 567-582**

Abstract.
"The optical paraxial ray equation for charged particles, including the effects of self fields, is discussed in both the laboratory and rotating Larmor frames. The corresponding beam envelope equation is derived, in the first instance for laminar flow but later for some non-laminar distributions. The equivalence between optical and hydrodynamical viewpoints is discussed in some detail, and the relation between pressure and emittance is explored. Finally, some of the characteristics of longitudinal energy spread in the beam are investigated."

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The last two terms only of equation (25) represent a beam in which the self force balances the centrifugal force. This can only happen when K is negative so that the inward magnetic force dominates. For a completely neutralized beam $K = -2\nu/\gamma$; writing $p_{\theta_0} = \beta_\perp \gamma m_0 c$ the last term becomes $(\beta_\perp/\beta)^2$, and the equilibrium condition is the familiar relation

$$\left(\frac{\beta_{\perp c}}{\beta}\right)^2 = \frac{2\langle\beta_\perp^2\rangle}{\beta^2} = \frac{2\nu}{\gamma}. \tag{27}$$

Sketches of the solutions corresponding to the various combinations of terms in equation (25), with λ independent of z, are shown in Fig. 2. Some, but not all, of these have been already discussed.

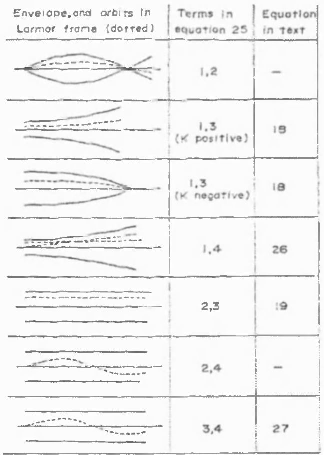

FIG. 2.—These curves represent solutions of the envelope equation (25) in which only two of the four terms are present. The dotted lines represent projections of typical trajectories in the Larmor frame.

In the discussion so far we have been concerned only with laminar beams. There is no distinction between an orbit model and a hydrodynamic model, the force per unit volume is just the number density times the force on a single particle. The beam is cold, and exerts no pressure.

Beams with finite pressure and temperature will now be described.

Figure A7.4: Optical & Hydrodynamical approaches to charged particle beams, p. 574

In his accompanying post-it note annotation (March 2003) Dr. Lawson says this is: not an analogue, but two different view points – which enable a richer appreciation of the field to be obtained."

Example	Aim Quotations are from papers or *post-it notes* or ***replies to my queries***	Visual Matrix
Eg. 1 [12]	"I chose what seemed to be the simplest and most elegant layout." (Dr. Lawson, replying to my questionnaire of 04-10-2004)	4x5 matrix Row1: Physical representation of waves; Row2: quantum mechanical viewpoint; Row3: graphical sketch of wavefunctions; Row4: whether or not they are bound states
Eg. 2 [13]	To introduce a "physical viewpoint which enables a range of different phenomena to be seen." The main aim is to bridge the conceptual divides between "neighbouring fields of physics."	6x3 matrix Column 1 gives current distribution; Column 2 gives spectrum of values of cosθ; Column 3 gives the angular distribution of radiation observed at a great distance from the track
Eg. 3 [14]	"The principal results are tabulated as a set of formulae, judicious use of which should enable order of magnitude calculations to be made over a useful range of configurations."	5x3 matrix. Column 1 gives a physical representation of 5 different cavity configurations; Column 2 gives the mathematical equations governing the leak rates. Column 3 gives the mathematical equations governing the leak rates as the time tends to infinity
Eg. 4 [15]	*"not an analogue, but two different viewpoints – which enable a richer appreciation of the field to be obtained."* *(Post-it note annotation, March 2003)*	7x3 matrix Column 1 consists of 7 curves representing solutions of an envelope equation; Column 2 shows which two of the four terms of the envelope equation are present; Column 3 provides a reference to the relevant equation in the text of the paper.

[12] Dr. Lawson, 1950, "Waveguides and wave mechanics: Some Similarities and differences." Unpublished paper.
[13] Dr. Lawson, 1989, "Particle-Photon Interactions." Published in **CERN**, 1990.
[14] Dr. Lawson, 1965, "Some calculations on the pumping of trapped volumes." Published in **J. Of Sci Instrum**, 1966.
[15] Dr. Lawson, 1975, "Optical and Hydrodynamical approaches to charged particle beams." Published in **Plasma Physics**

A8.1 A Humorous Way of Highlighting The Sub-Cultures of Physics

Problem: To Catch a Lion in the Sahara Desert

Hunting lions in Africa was originally published as "A contribution to the mathematical theory of big game hunting" in the American Mathematical Monthly in 1938 by "H. Petard, of Princeton NJ" [actually the late Ralph Boas]. It has become a classic physics joke and can be found in numerous locations on-line. [16]

Theoretical Physics Methods

1) The Dirac method: We assert that wild lions can ipso facto not be observed in the Sahara desert. Therefore, if there are any lions at all in the desert, they are tame. We leave catching a tame lion as an exercise to the reader.
2) The Schrödinger method: At every instant there is a non-zero probability of the lion being in the cage. Sit and wait.
3) The Quantum Measurement Method: We assume that the sex of the lion is _ab initio_ indeterminate. The wave function for the lion is hence a superposition of the gender eigenstate for a lion and that for a lioness. We lay these eigenstates out flat on the ground and orthogonal to each other. Since the (male) lion has a distinctive mane, the measurement of sex can safely be made from a distance, using binoculars. The lion then collapses into one of the eigenstates, which is rolled up and placed inside the cage.
4) The nuclear physics method: Insert a tame lion into the cage and apply a Majorana exchange operator on it and a wild lion. As a variant let us assume that we would like to catch (for argument's sake) a male lion. We insert a tame female lion into the cage and apply the Heisenberg exchange operator, exchanging spins.
5) The Newton method: Cage and lion attract each other with the gravitation force. We neglect the friction. This way the lion will arrive sooner or later in the cage.
6) The Special relativistic method: One moves over the desert with light velocity. The relativistic length contraction makes the lion flat as paper. One takes it, rolls it up and puts a rubber band around the lion.
7) The general relativistic method: All over the desert we distribute lion bait containing large amounts of the companion star of Sirius. After enough of the bait has been eaten we send a beam of light through the desert. This will curl around the lion so it gets all confused and can be approached without danger.
8) The Heisenberg method: Position and Velocity from a moving lion cannot be measure at the same time. As moving lions have no physical meaningful position in the desert, one cannot catch them. The lion hunt can therefore be limited to resting lions. The catching of a resting, not moving lion is left as an exercise for the reader.

Experimental Physics Methods

1) The thermodynamics method: We construct a semi-permeable membrane which lets everything but lions pass through. This we drag across the desert.
2) The atomic fission method
We irradiate the desert with slow neutrons. The lion becomes radioactive and starts to disintegrate. Once the disintegration process is progressed far enough the lion will be unable to resist.
3) The magneto-optical method: We plant a large, lens shaped field with cat mint (nepeta cataria) such that its axis is parallel to the direction of the horizontal component of the earth's magnetic field. We put the cage in one of the field's foci. Throughout the desert we distribute large amounts of magnetized spinach (spinacia oleracea) which has, as everybody knows, a high iron content. The spinach is eaten by vegetarian desert inhabitants which in turn are eaten by the lions. Afterwards the lions are oriented parallel to the earth's magnetic field and the resulting lion beam is focussed on the cage by the cat mint lens.

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[16] For example, on the home page of Prof. Reinhard Schumacher, Department of Physics, Carnegie Mellon University: http://www-meg.phys.cmu.edu/physics_33211/Relativity_gags.txt (Accessed 26-01-2006)